# Physics at Hadron Colliders

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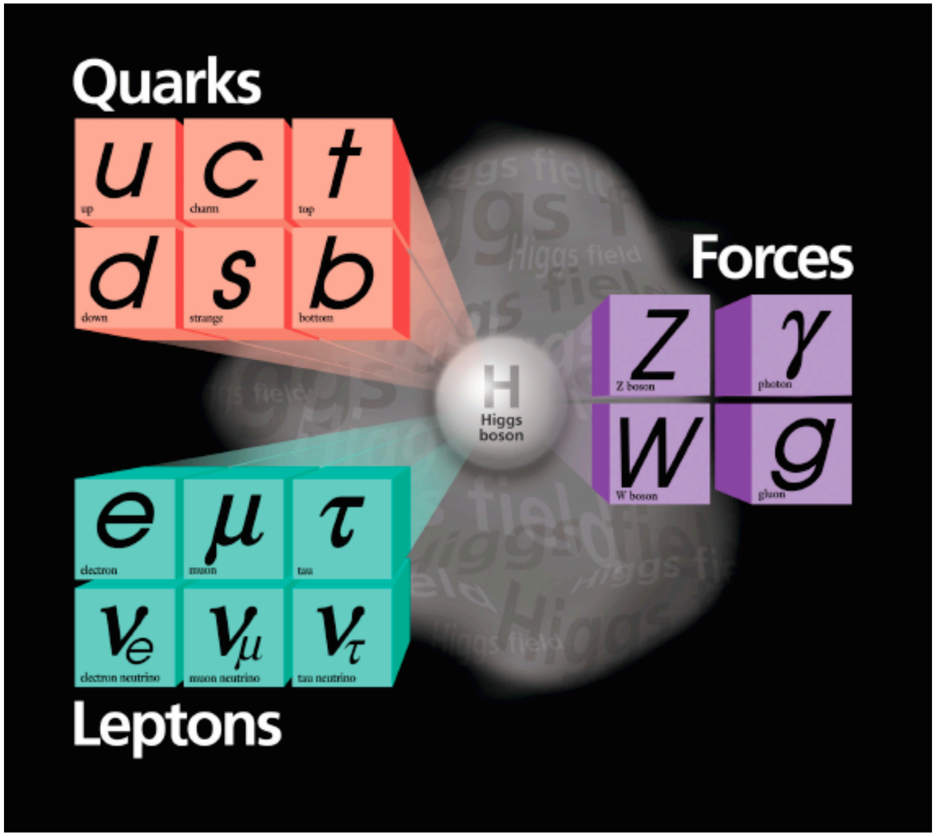
# Outline

- **Lecture I: Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current and near future colliders: Tevatron and LHC
  - Hadron-hadron collisions
- **Lecture II: Standard Model Measurements**
  - Tests of QCD
  - Precision measurements in electroweak sector
- **Lecture III: Searches for the Higgs Boson**
  - Standard Model Higgs Boson
  - Higgs Bosons beyond the Standard Model
- **Lecture IV: Searches for New Physics**
  - Supersymmetry
  - High Mass Resonances (Extra Dimensions etc.)

# Outstanding Problems in Particle Physics
## and the role of Hadron Colliders

# Fundamental Particles and Forces




- **Matter**
  - is made out of fermions
- **Forces**
  - are mediated by bosons
- **Higgs boson**
  - breaks the electroweak symmetry and gives mass to fermions and weak gauge bosons

**Amazingly successful in describing precisely data from all collider experiments**

# The Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\!\!\!/\,\psi$$
$$+ \psi_i \lambda_{ij} \psi_j h + \text{h.c.}$$
$$+ |D_\mu h|^2 - V(h)$$
$$+ \frac{1}{M} L_i \lambda^\nu_{ij} L_j h^2 \text{ or } L_i \lambda^\nu_{ij} N_j$$

gauge sector ✓

flavour sector ✓

EWSB sector ✓

ν mass sector

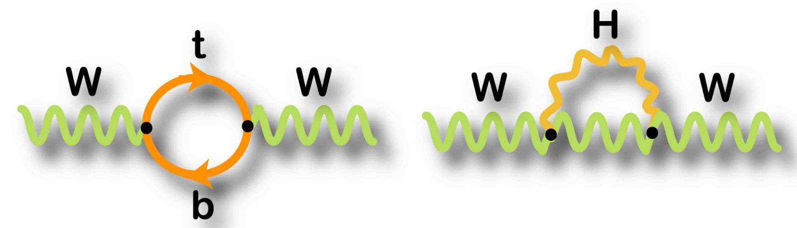
… and beyond?

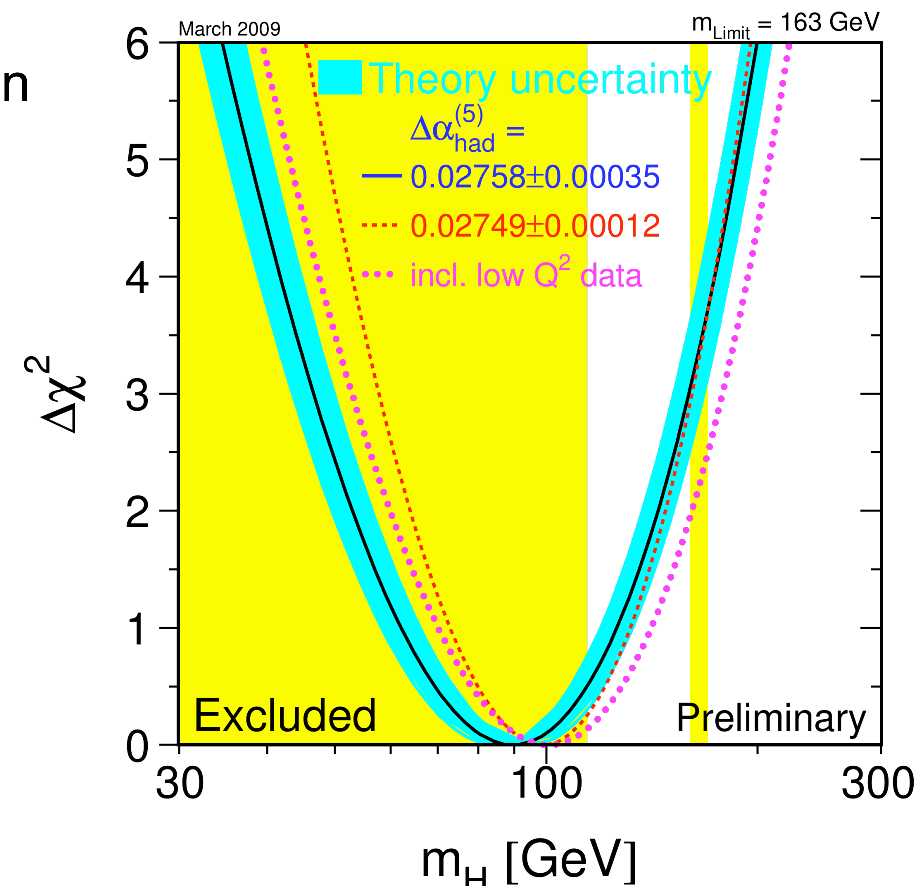
supersymmetry (many variants)
extra spacetime dimensions ✓
compositeness
strong electroweak symmetry breaking
…
something new?!

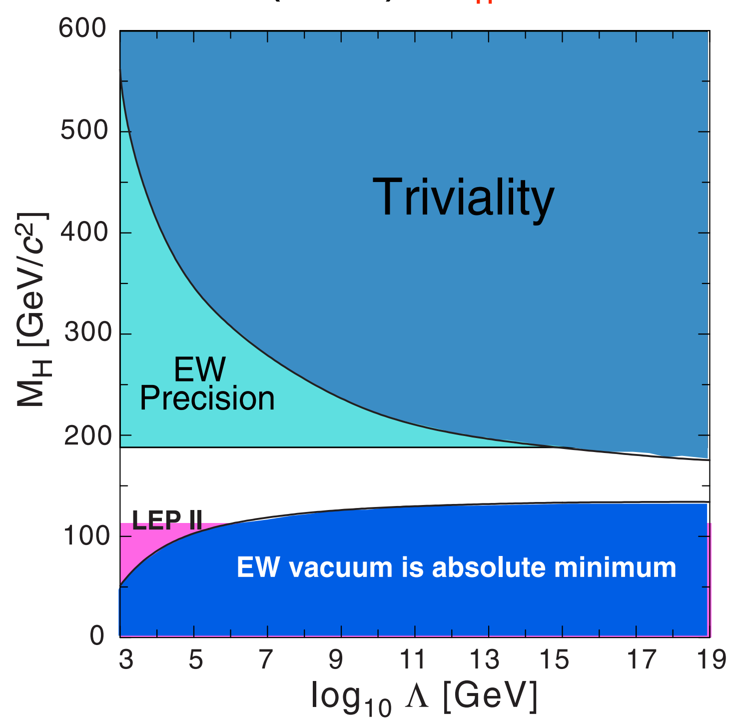
*[W. J. Stirling]*

# Problem I: Where is the Higgs boson?

- Precision measurements of
  - $M_W = 80.399 \pm 0.023$ GeV/$c^2$
  - $M_{top} = 173.1 \pm 1.2$ GeV/$c^2$
  - Precision measurements on Z pole
- Prediction of higgs boson mass within SM due to loop corrections
  - Most likely value: $90^{+36}_{-27}$ GeV
- Direct limit (LEP): $m_h > 114.4$ GeV

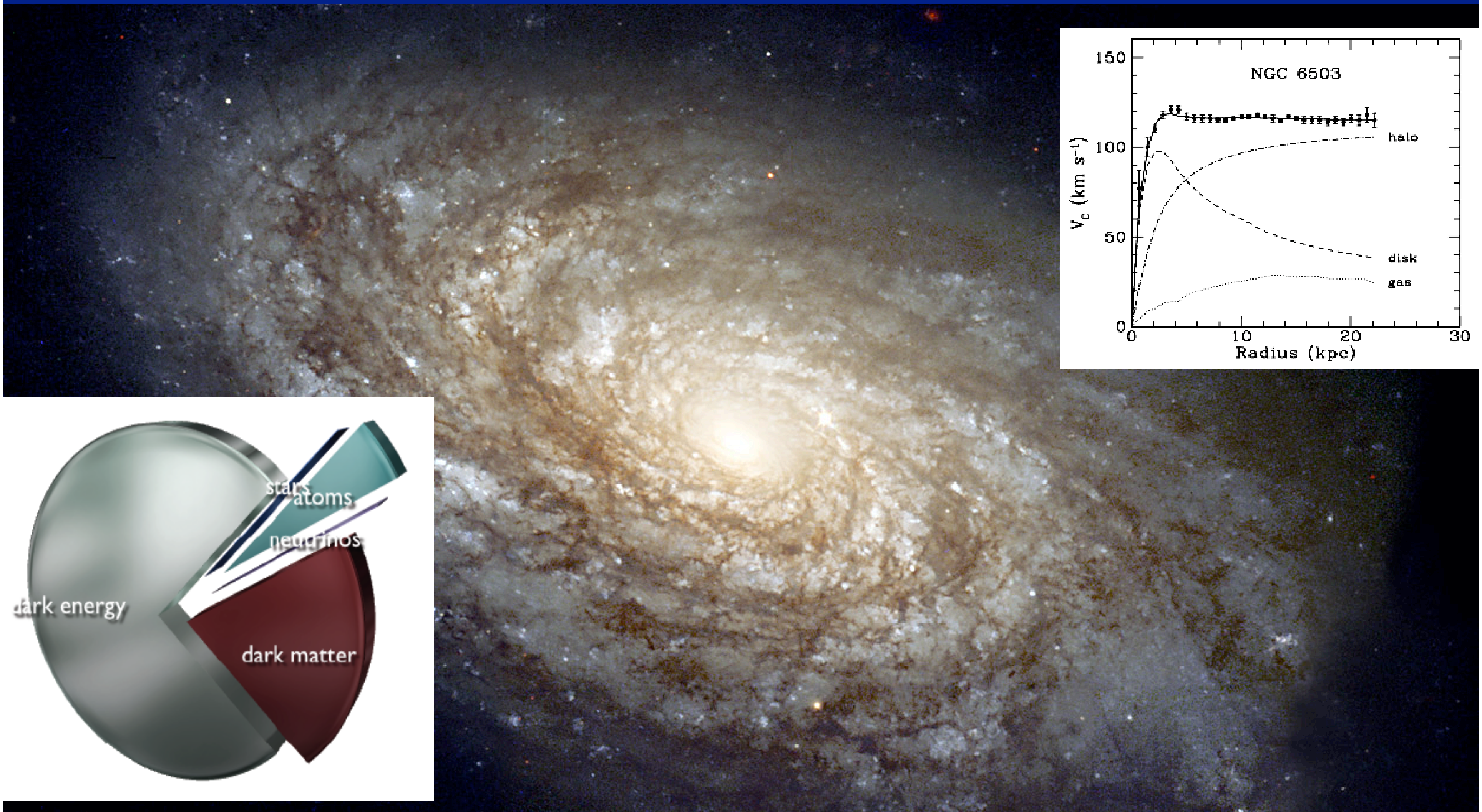



- $m_H < 163$ GeV @95%CL

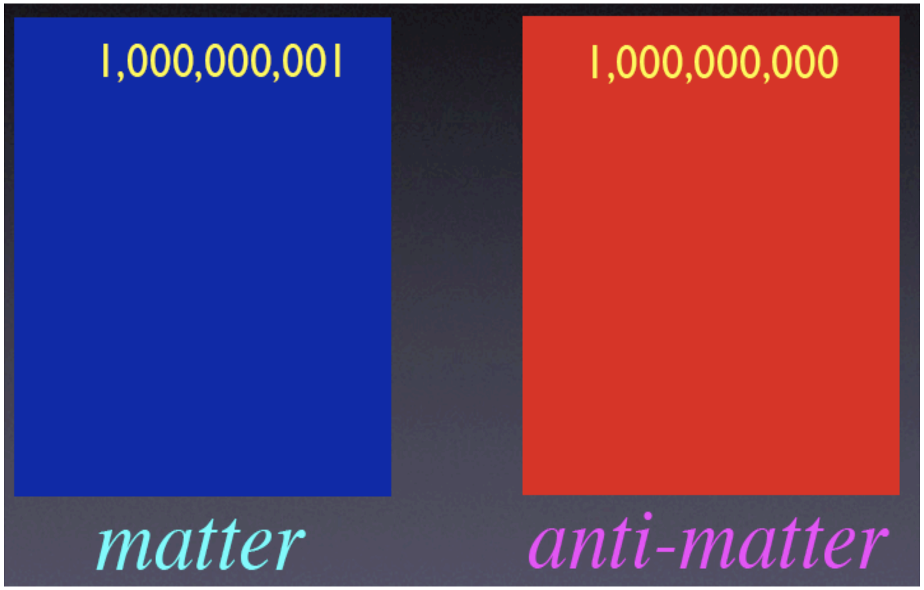
# Problem II: What is the Dark Matter?

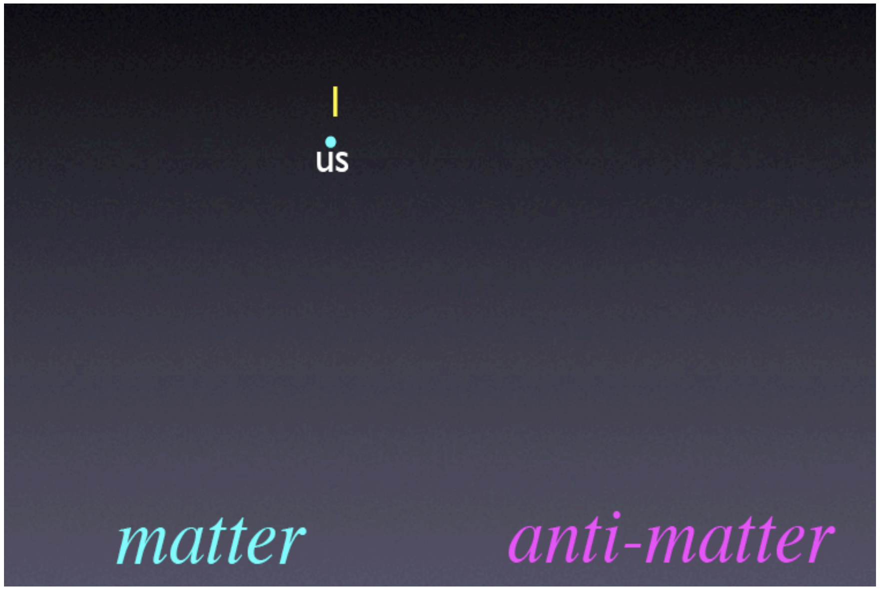



**Standard Model only accounts for 20% of the matter of the Universe**

$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

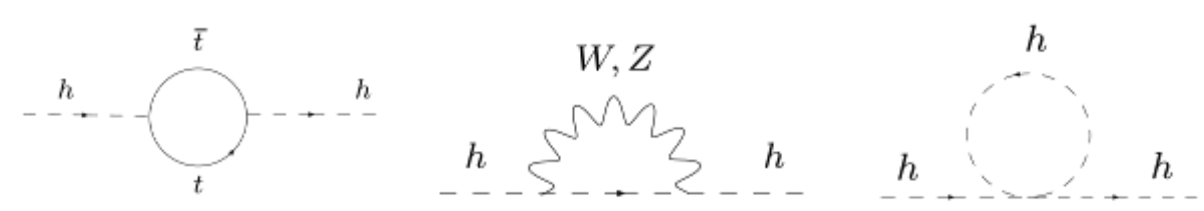
# Problem III:
# Where did all the Antimatter go?



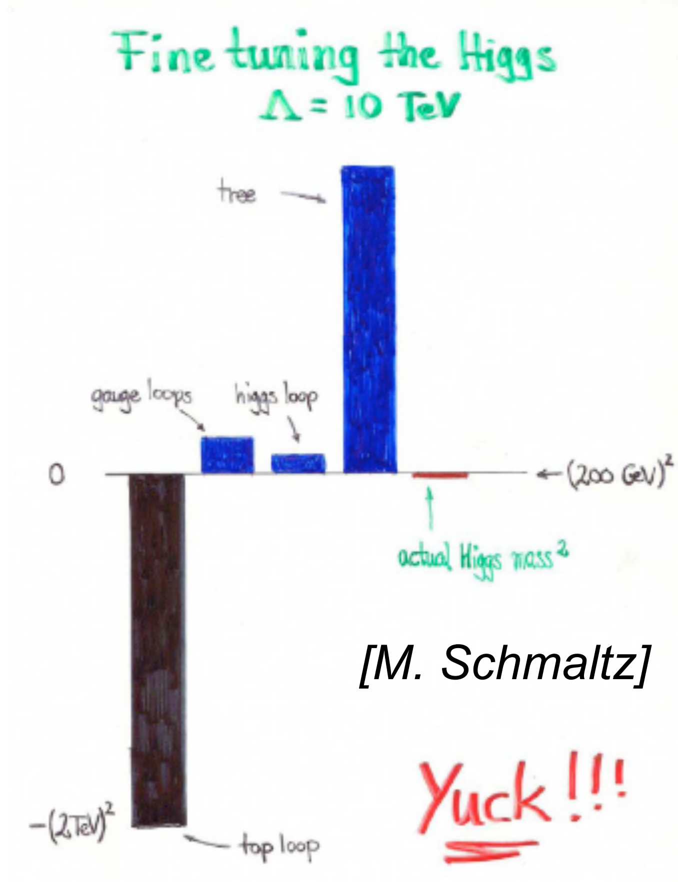

- **Not explained by Standard Model**

# Problem IV: Hierarchy Problem




$$m^2_H \approx (200\ \text{GeV})^2 = m^2_H{}^{\text{tree}} + \delta\, m^2_H{}^{\text{top}} + \delta\, m^2_H{}^{\text{gauge}} + \delta\, m^2_H{}^{\text{higgs}}$$

- **Why is gravity so weak?**
  - $M_W/M_{Planck} \sim 10^{16}$ or $G_F/G_N \sim 10^{32}$!
  - Free parameter $m^2_H{}^{tree}$ needs to be "finetuned" to cancel huge corrections
- Can be solved by presence of **new particles at M ~1 TeV**
  - Already really bad for M~10 TeV

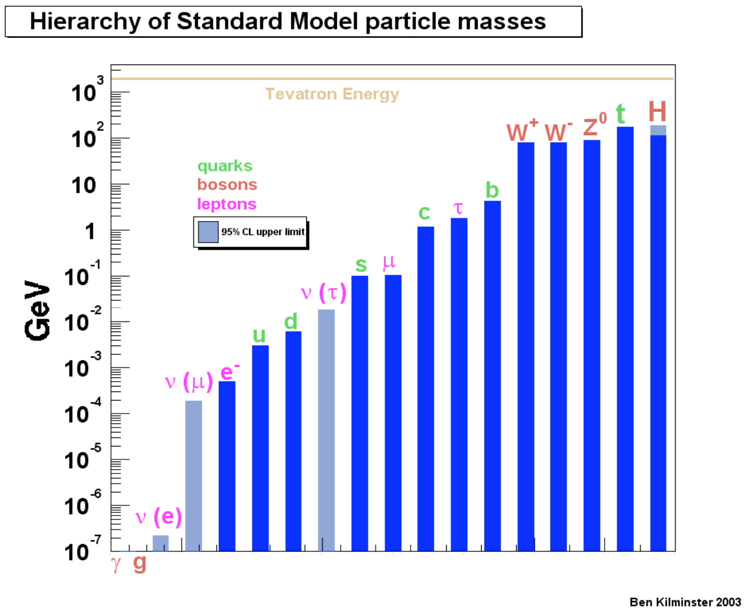


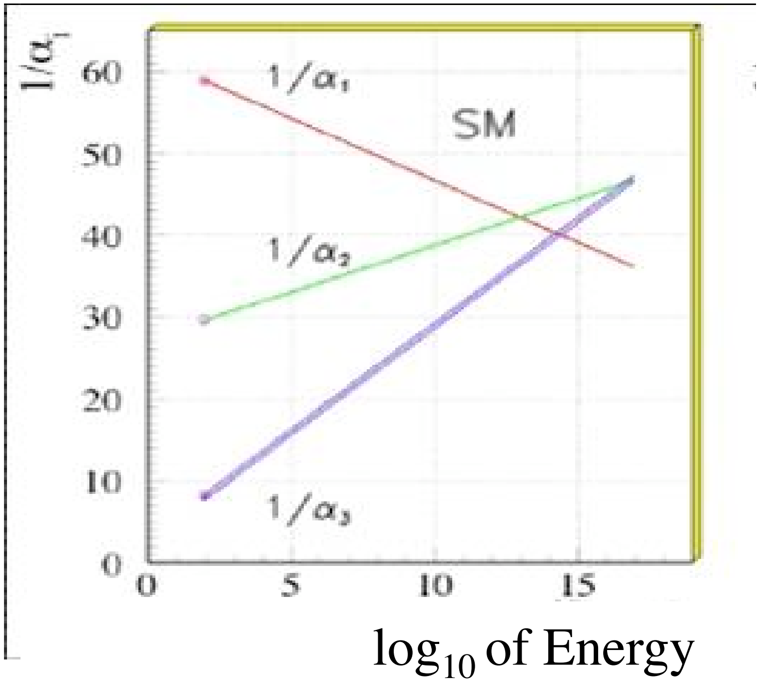

[M. Schmaltz]

# (Some) More Problems …

- **Matter:**
  - SM cannot explain **number of fermion generations**
  - or their **large mass hierarchy**
    - $m_{top}/m_{up}$~100,000
- **Gauge forces:**
  - electroweak and strong **interactions do not unify** in SM
  - SM has no concept of **gravity**
- **What is Dark Energy?**

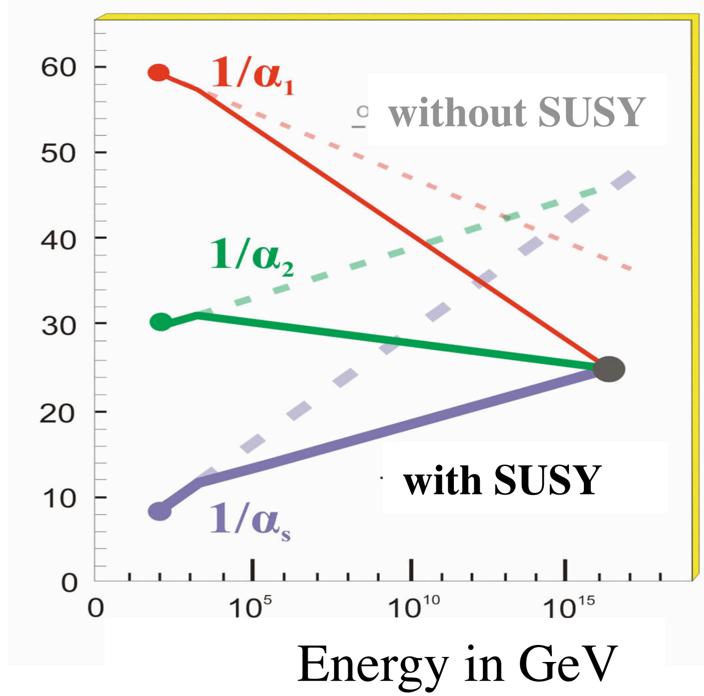
**"Supersymmetry" (SUSY) can solve some of these problems**

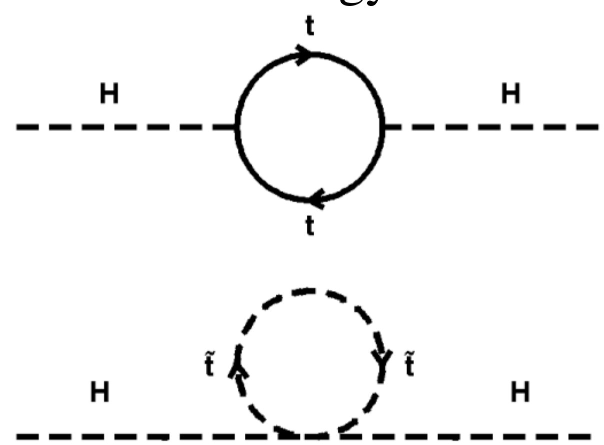


# SUSY can solve some problems

- Supersymmetry (SUSY)
  - Each SM particle gets a partner differing in spin by 1/2
- Unifications of forces possible
  - SUSY changes running of couplings
- Dark matter candidate exists:
  - The lightest neutral partner of the gauge bosons
- No (or little) fine-tuning required
  - Radiative corrections to Higgs acquire SUSY corrections
    - Cancellation of fermion and sfermion loops



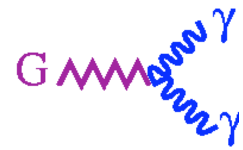




**Mass of supersymmetric particles must not be too high (~TeV)**

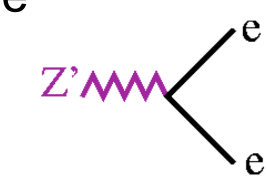
# Beyond Supersymmetry

- **Strong theoretical prejudices for SUSY being true**
  - But so far there is a lack of SUSY observation….

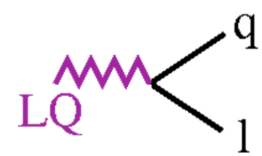
- **Need to keep an open eye for e.g.:**
  - **Extra spatial dimensions:**
    - Addresses hierarchy problem: make gravity strong at TeV scale



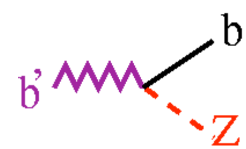

  - **Extra gauge groups: Z', W'**
    - Occur naturally in GUT scale theories




  - **Leptoquarks:**
    - Would combine naturally the quark and lepton sector

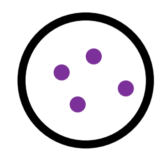



  - **New/excited fermions**
    - More generations? Compositeness?





  - **Preons:**
    - atom⇒nucleus ⇒ proton/neutron ⇒ quarks ⇒ preons?



  - **… ????**: something nobody has thought of yet

# Confusion among Theorists?

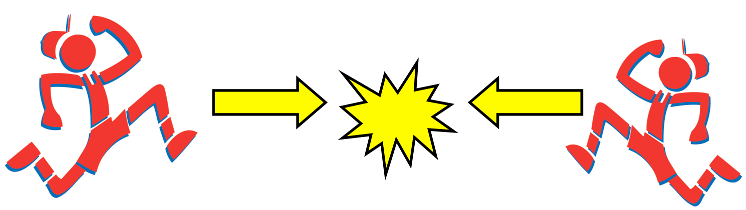
*[Hitoshi Murayama]*


**Need experiments to figure out which (if any) represents Nature**

# Why a Hadron Collider?

- Disadvantages:
  - Hadrons are complex objects
    - High multiplicity of other stuff
    - Energy and type of colliding parton (quark, gluon) unknown
      - Kinematics of events not fully constrained
- Advantage:
  - Can access higher energies

**Lepton Collider**
(collision of two point-like particles)



**Hadron collider**
(collision of ~50 point-like particles)

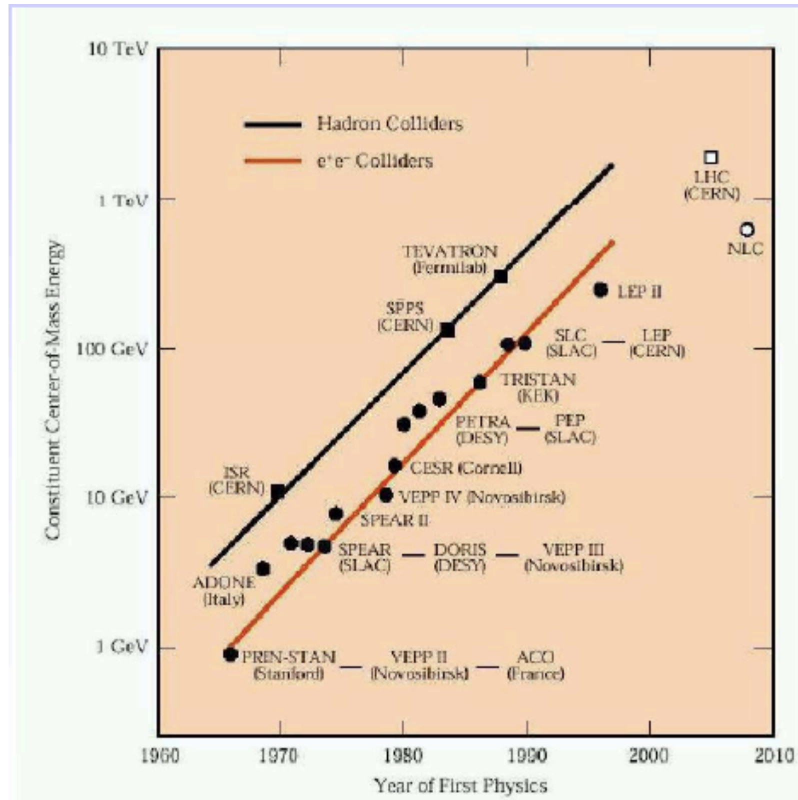
*[Karl Jakobs]*

# e⁺e⁻ vs Hadron Colliders

- Circular colliders:
  - Pro:
    - Reuse their power on each turn
  - Con:
    - Synchrotron radiation reduces energy of particles
      - Problem worsens with $m^4$
- Linear colliders:
  - Particle sees each component just once
  - Now more cost-effective for electrons than circular collider => proposal of *ILC* (=International Linear Collider)

Energy loss per turn: $$-\Delta E \approx \frac{4\,\pi\,e^2}{3\,R}\left(\frac{E}{mc^2}\right)^4$$

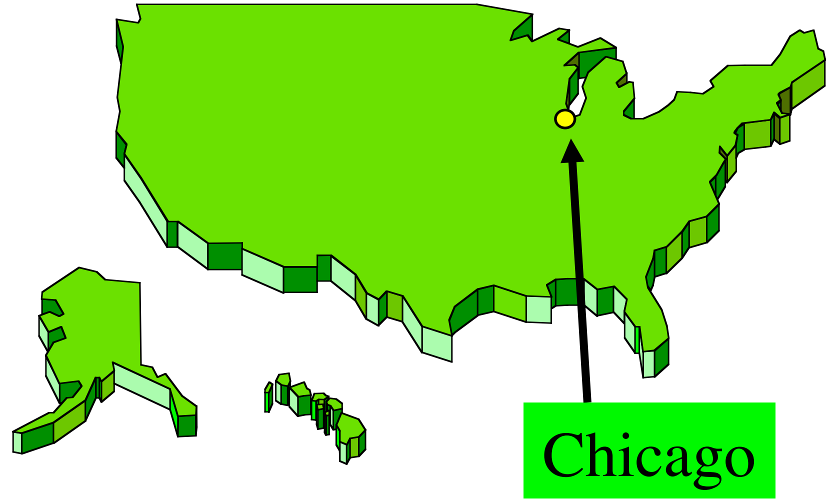
Energy loss: e vs p $$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$



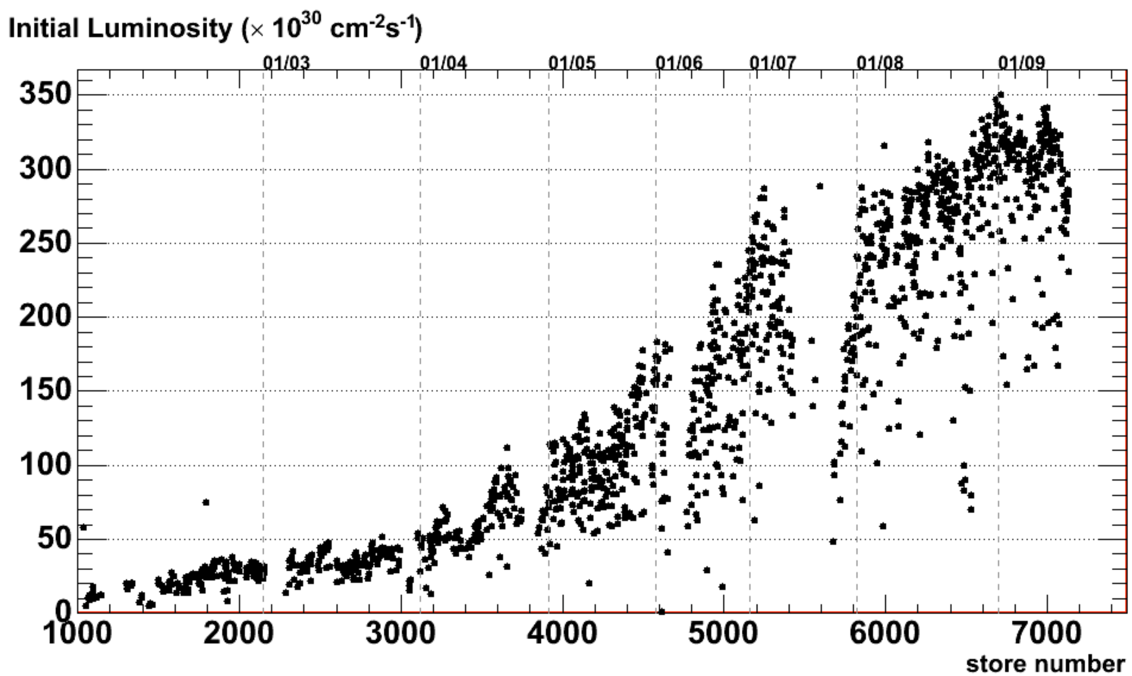
# Current Hadron Colliders:
# Tevatron and LHC

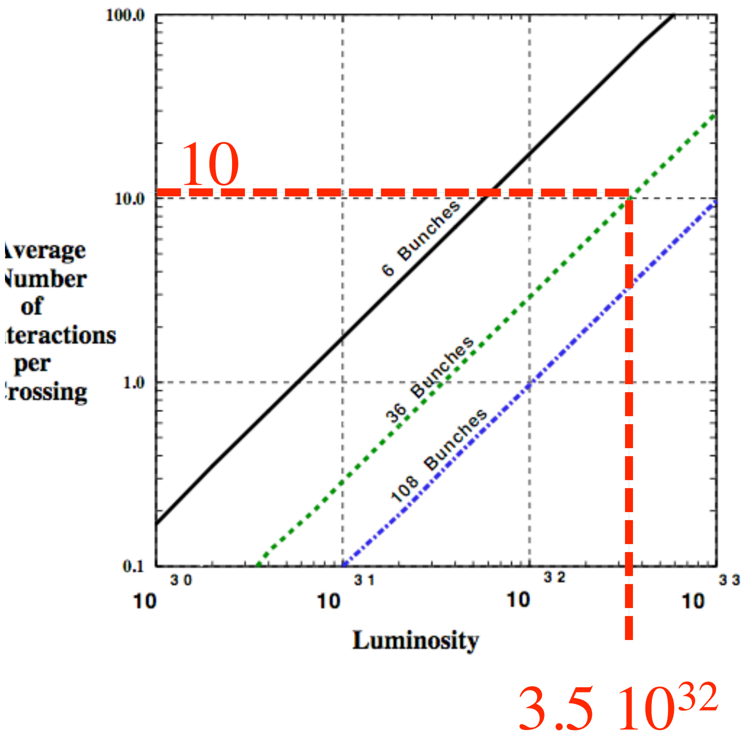
# The Tevatron

- $p\bar{p}$ collider:
  - 6.5 km circumference
  - Beam energy: 980 GeV
    - $\sqrt{s}$=1.96 TeV
  - 36 bunches:
    - Time between bunches: $\Delta t$=396 ns
- Main challenges:
  - Anti-proton production and storage
  - Irregular failures:
    - Quenches
- CDF and DØ experiments:
  - 700 physicists/experiment



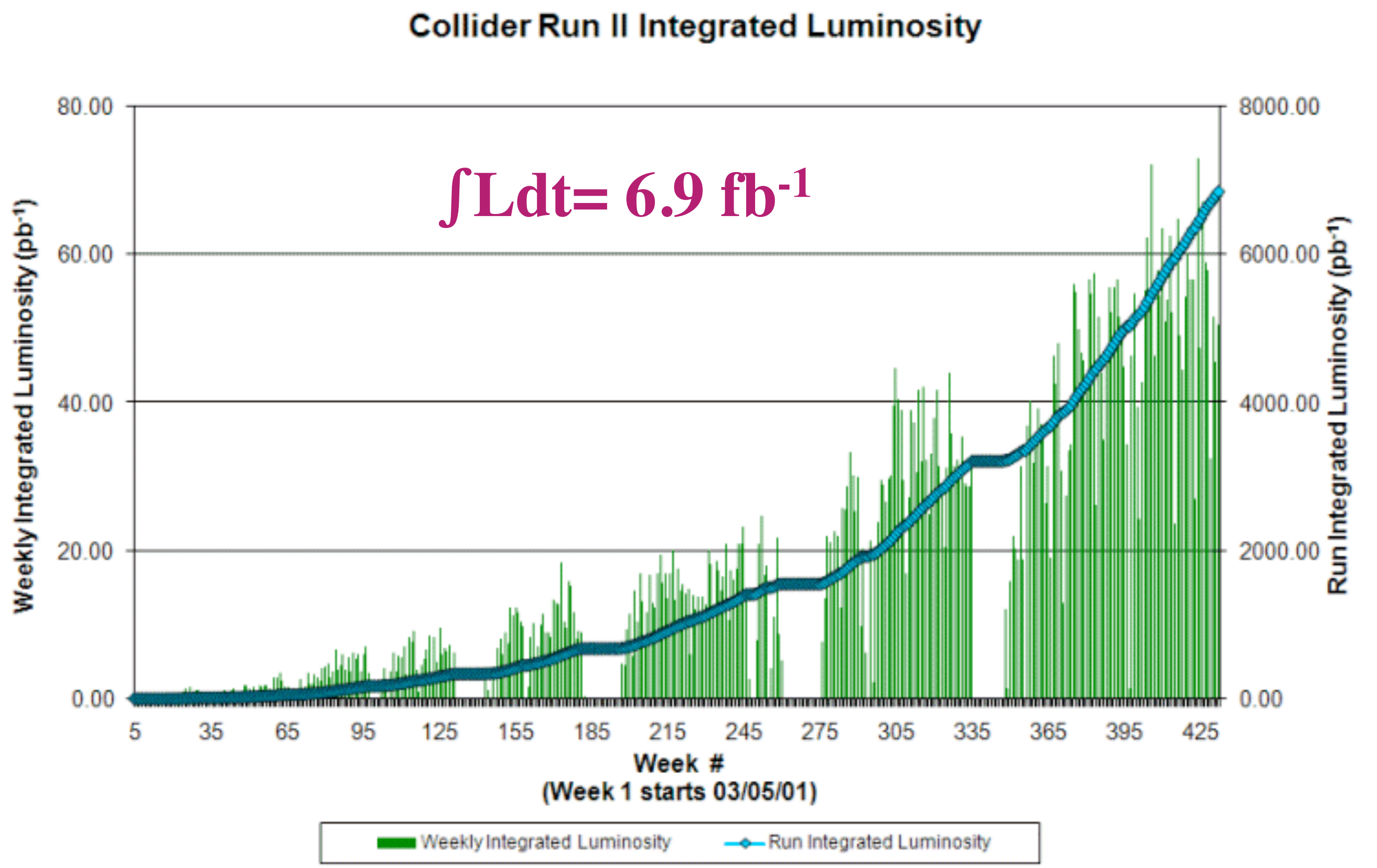

# Tevatron Instantaneous Luminosity




- peak luminosity of $3.5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- corresponds to about 10 interactions per crossing

# Tevatron Integrated Luminosity



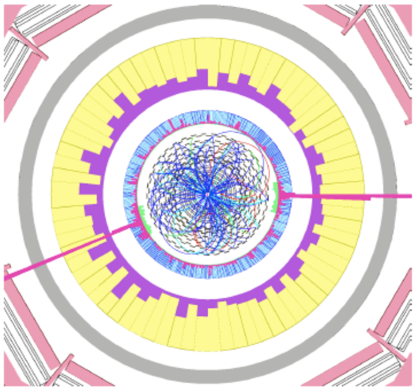

$$N_{event} = \text{cross section} \times \int L dt \times \text{Efficiency}$$

Given by Nature
(calculated by theorists)

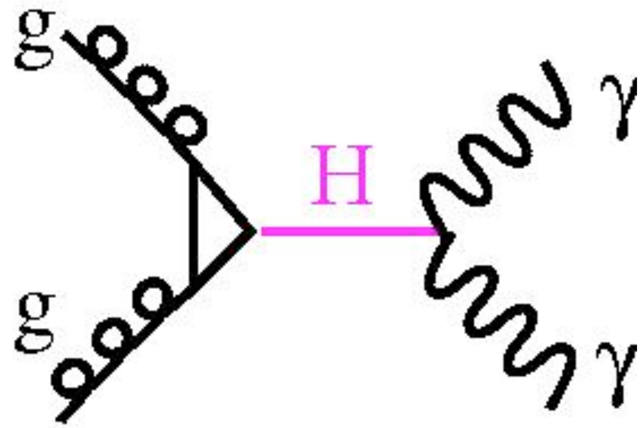
accelerator

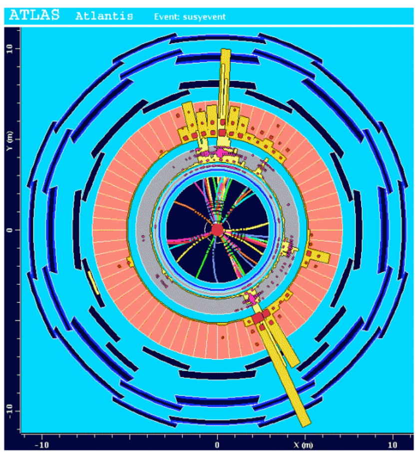
Detector
(Experimentalist)

# The Experimental Challenge

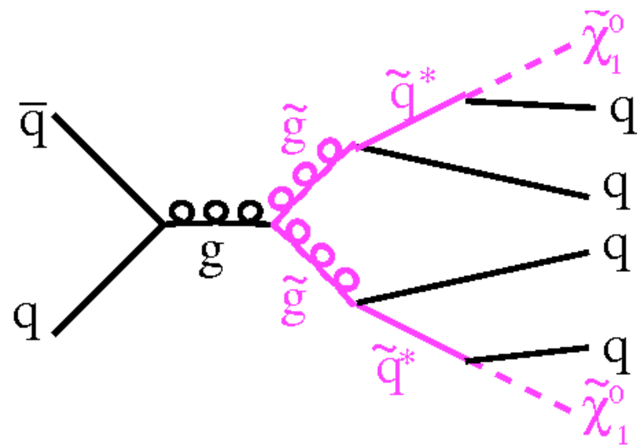


Higgs



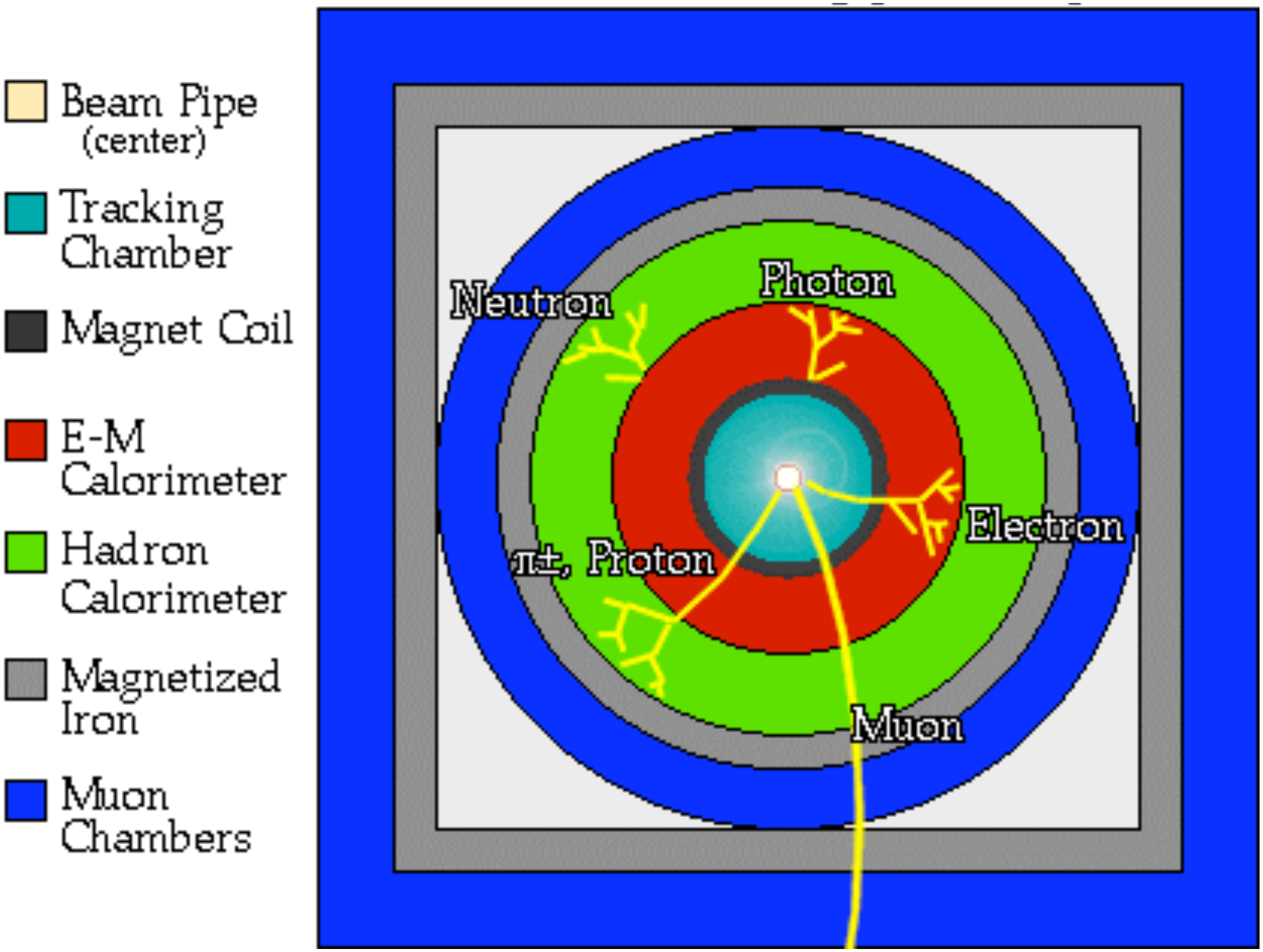

Supersymmetry




- **Measured hits in detector**
- **=> use hits to reconstruct particle paths and energies**
- **=> estimate background processes**
- **=> understand the underlying physics**

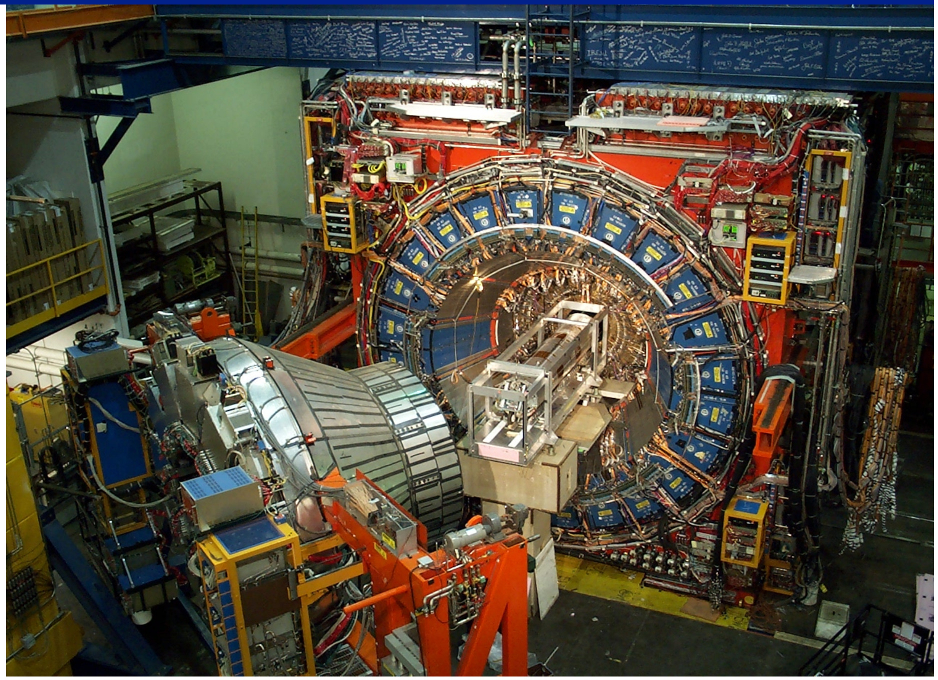
# Particle Identification

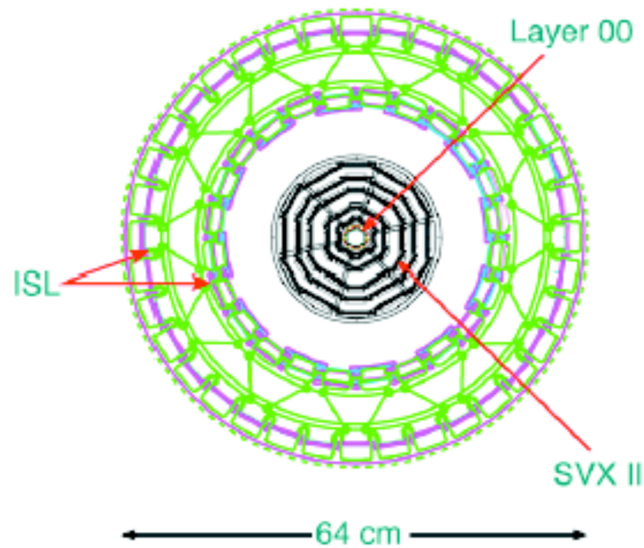
Detector designed to separate electrons, photons, muons, neutral and charged hadrons



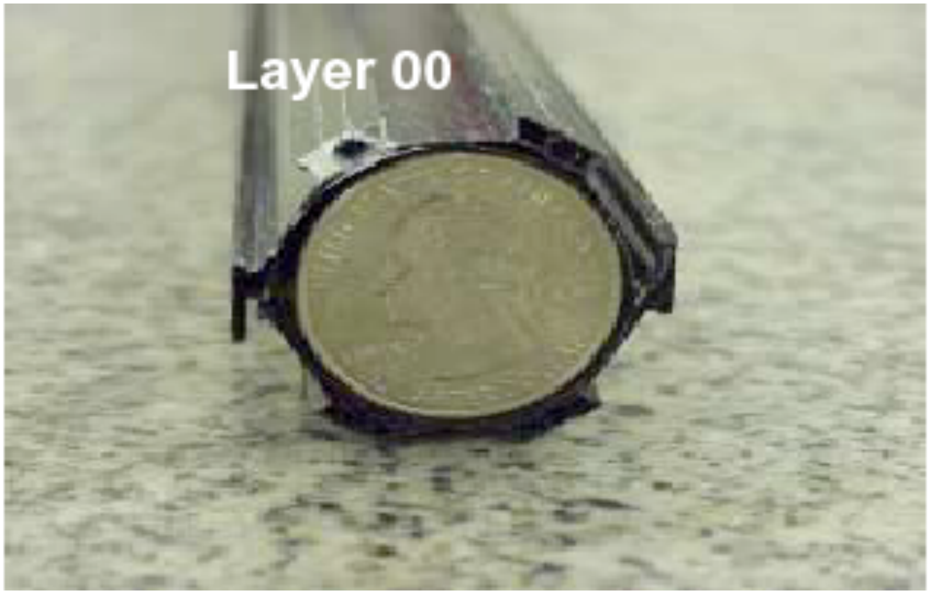
# CDF

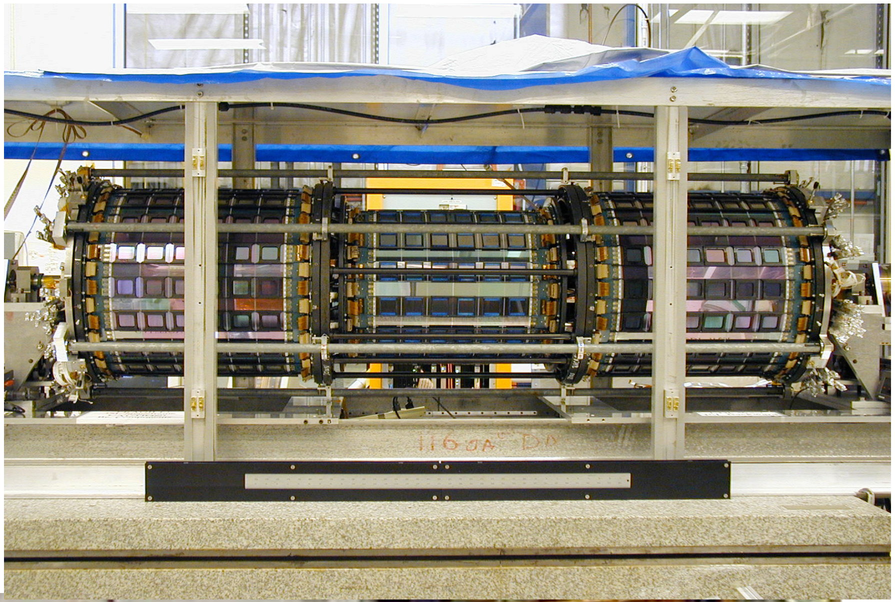
- Core detector operates since 1985:
  - Central Calorimeters
  - Central muon chambers
- Major upgrades for Run II:
  - Drift chamber: COT
  - Silicon: SVX, ISL, L00
    - 8 layers
    - 700k readout channels
    - 6 $m^2$
    - material:15% $X_0$
  - Forward calorimeters
  - Forward muon system
    - Improved central too
  - Time-of-flight
  - Preshower detector
  - Timing in EM calorimeter
  - Trigger and DAQ

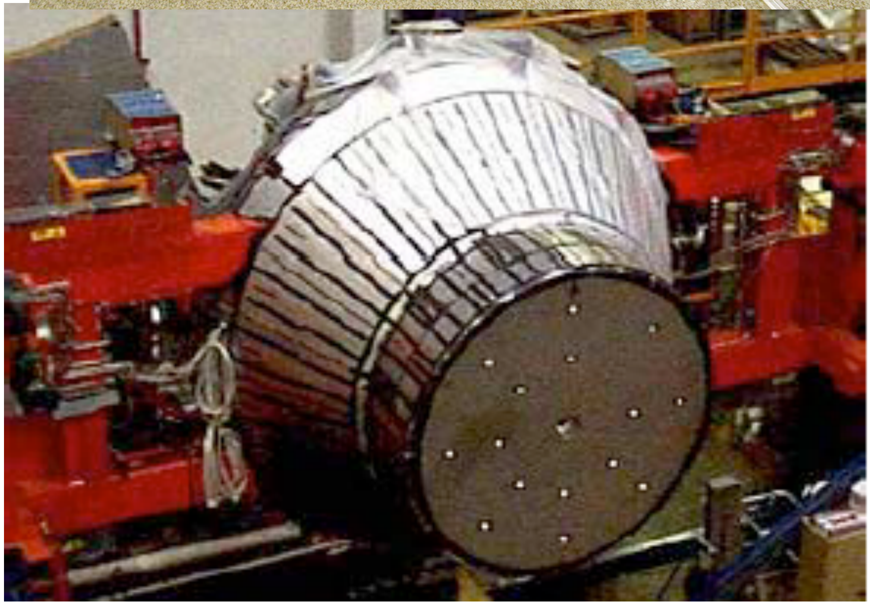




# Some new CDF Subdetectors



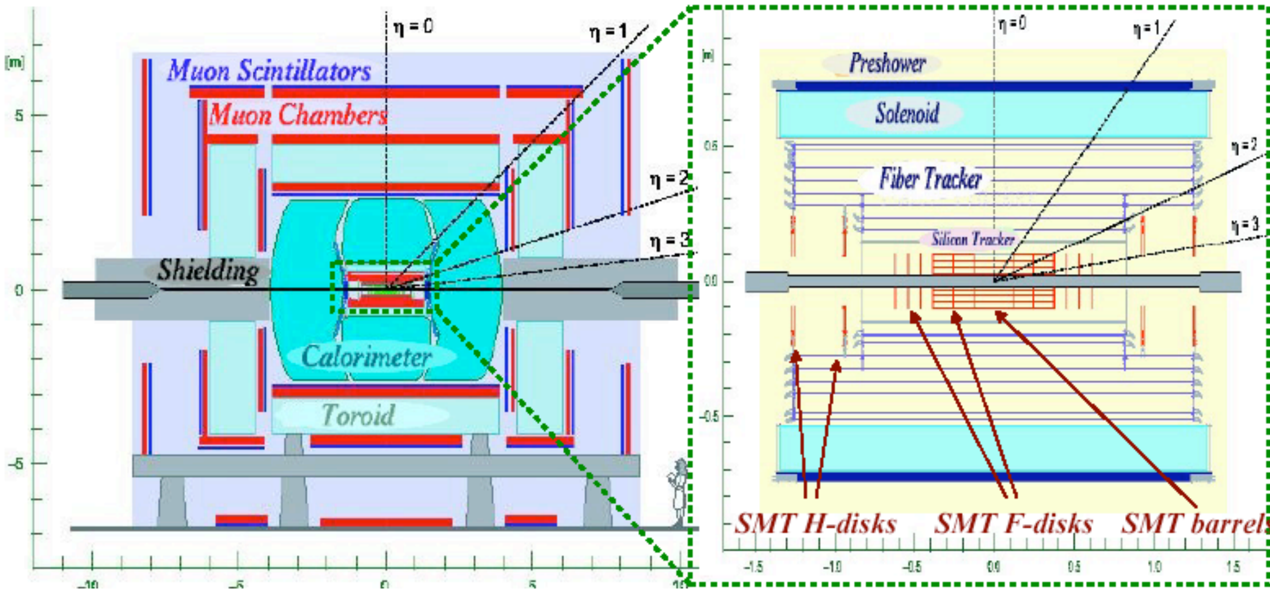





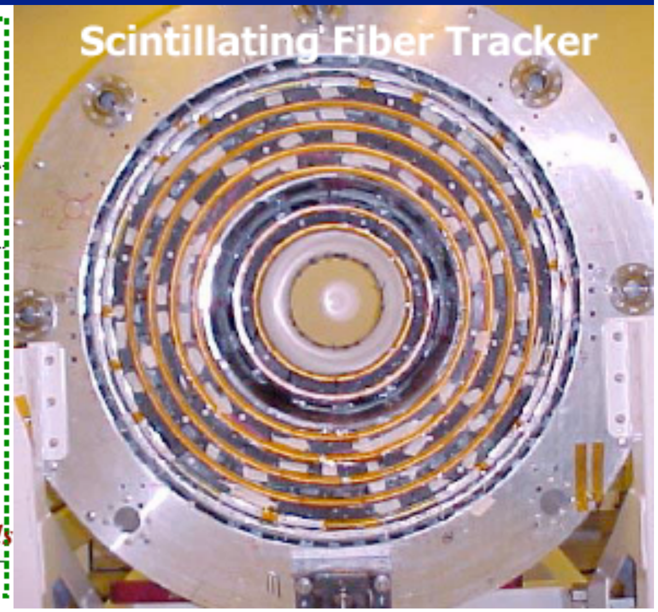
# DØ Detector

- Retained from Run I
  - Excellent muon coverage
  - Compact high granularity LAr calorimeter
- New for run 2:
  - 2 Tesla magnet
  - Silicon detector
  - Fiber tracker
  - Trigger and Readout
  - Forward roman pots

# DØ Detector



Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
η = 0
η = 1
η = 2
η = 3
[m]
Preshower
Solenoid
Fiber Tracker
Silicon Tracker
SMT H-disks
SMT F-disks
SMT barrels

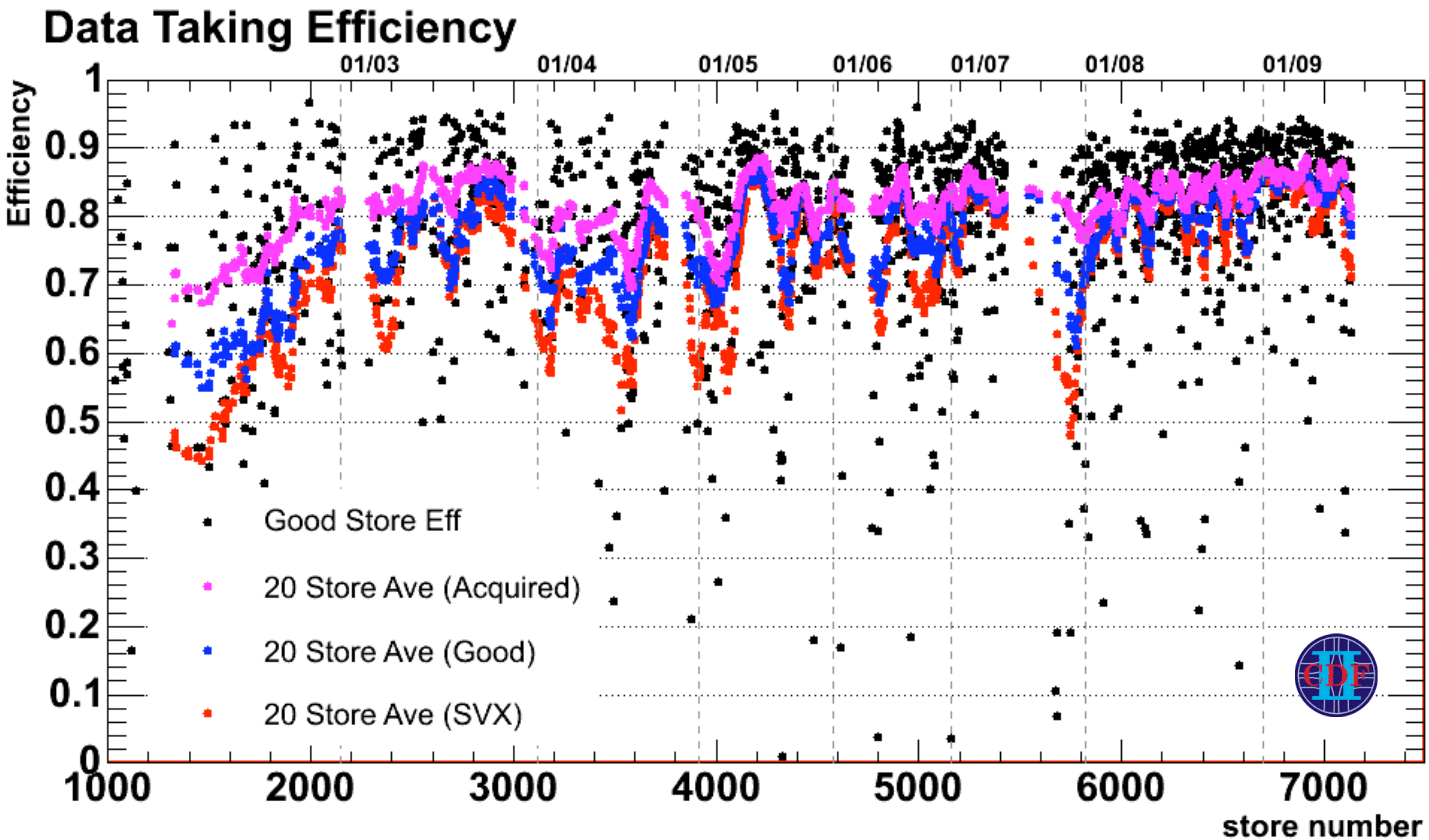



Scintillating Fiber Tracker


Silicon Microstrip Tracker

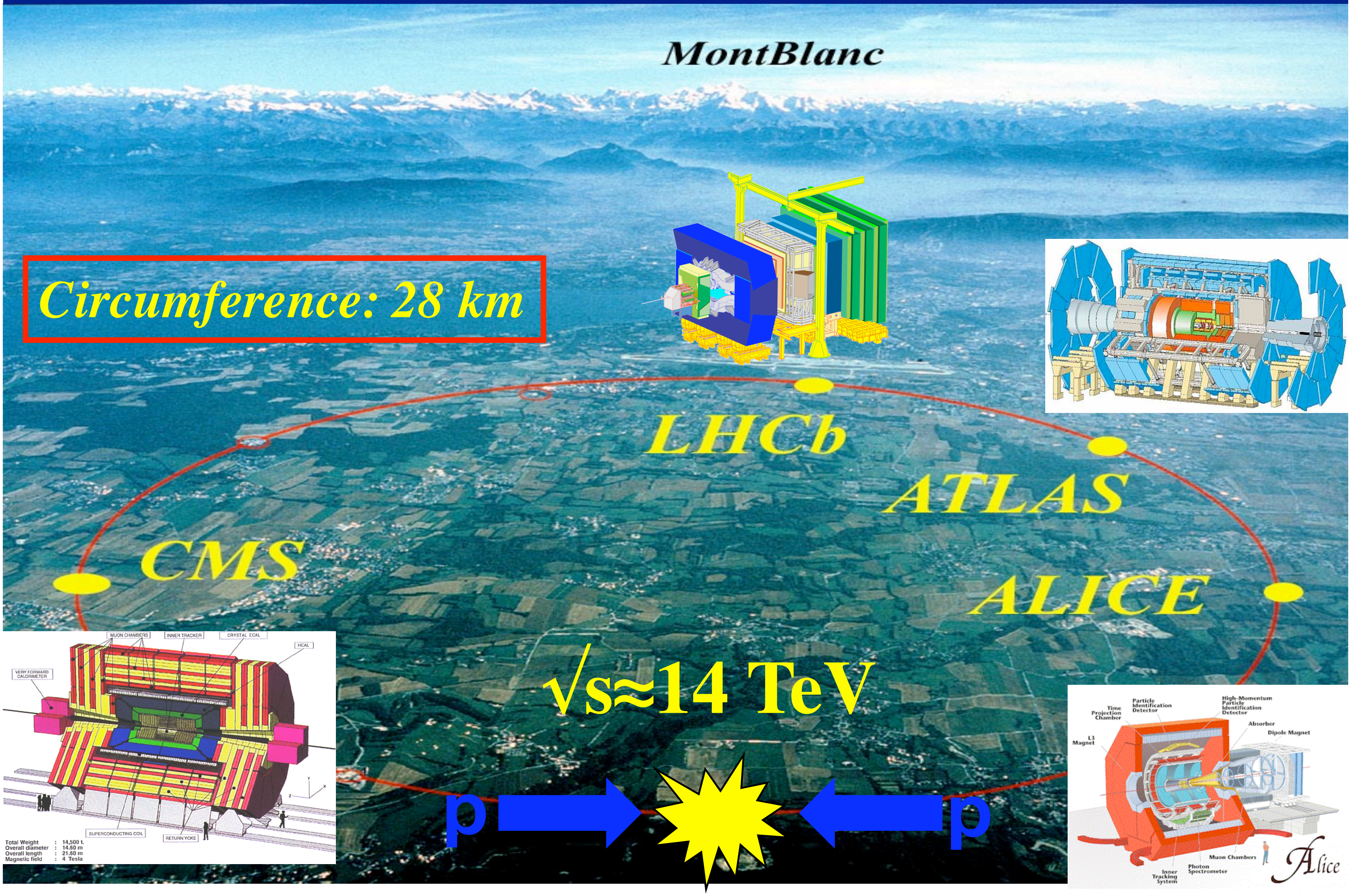

Superconducting
Solenoid

# Detector Operation




- Data taking efficiency about 75-85%
  - Depending on which components are needed for analysis

# The Large Hadron Collider (LHC)

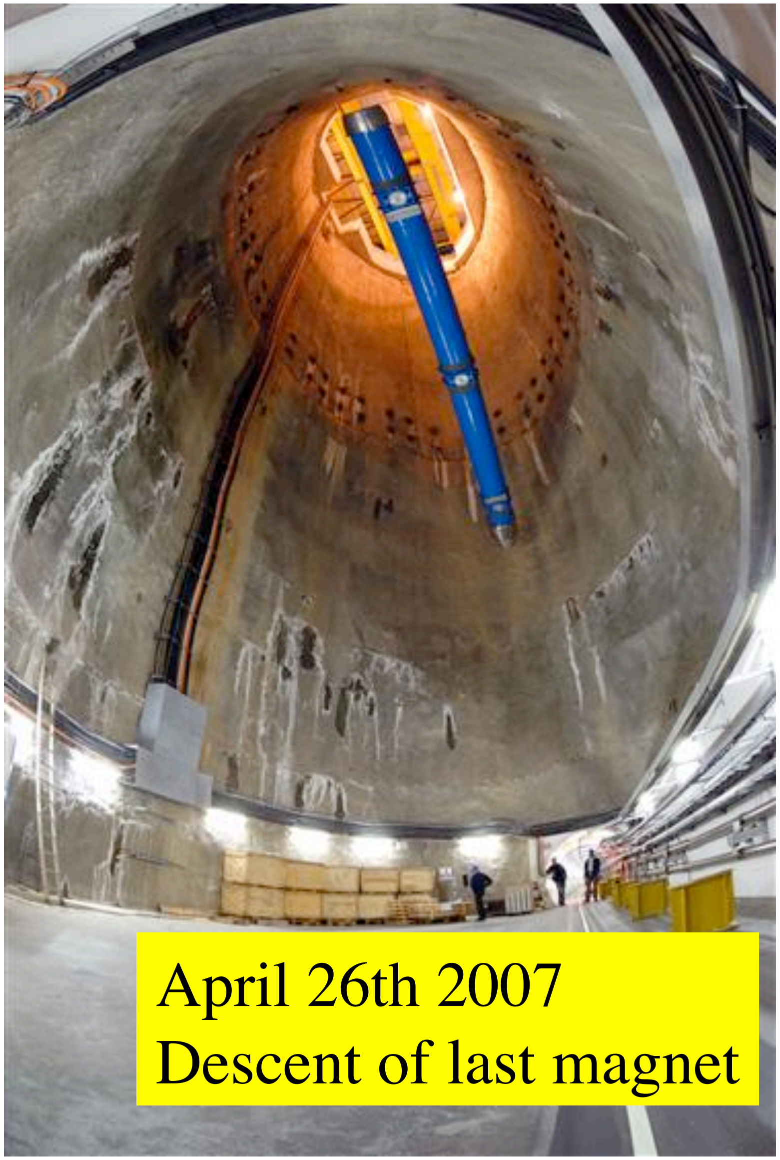


# LHC Machine Parameters

| | **LHC (design)** | Tevatron (achieved) |
|---|---|---|
| Centre-of-mass energy | **14 TeV** | 1.96 TeV |
| Number of bunches | **2808** | 36 |
| Bunch spacing | **25 ns** | 396 ns |
| Energy stored in beam | **360 MJ** | 1 MJ |
| Peak Luminosity | **$10^{33}$-$10^{34}$ cm$^{-2}$s$^{-1}$** | 3.5 x $10^{32}$ cm$^{-2}$s$^{-1}$ |
| Integrated Luminosity / year | **10-100 fb$^{-1}$** | ~2 fb$^{-1}$ |

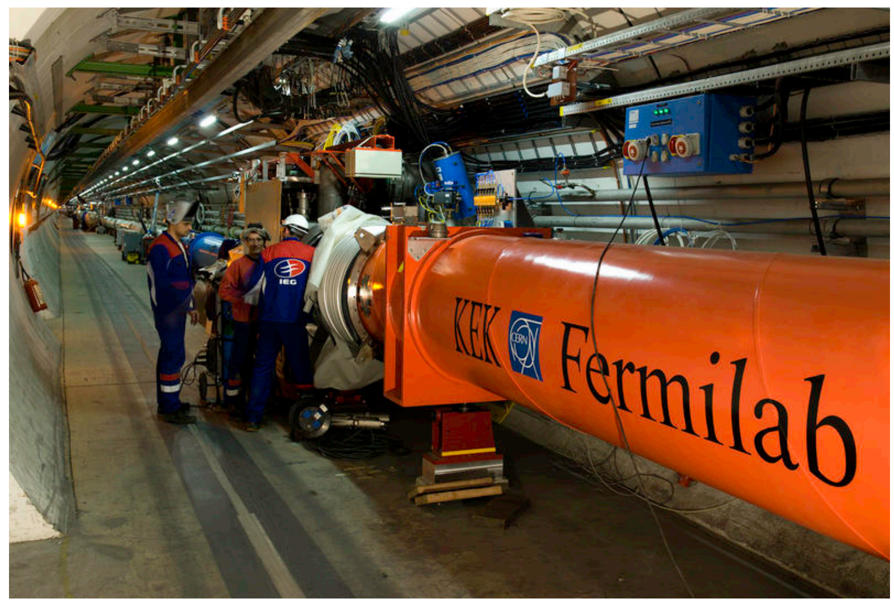
- Factor of ~1000 more powerful than Tevatron
  - 7 times more energy
  - Factor 3-30 times more luminosity
  - Physics cross sections factor 10-1000 larger
- First collisions planned for end of 2009
  - Aims to reach $\sqrt{s}$=8-10 TeV in the 2009/2010 run

# LHC Construction

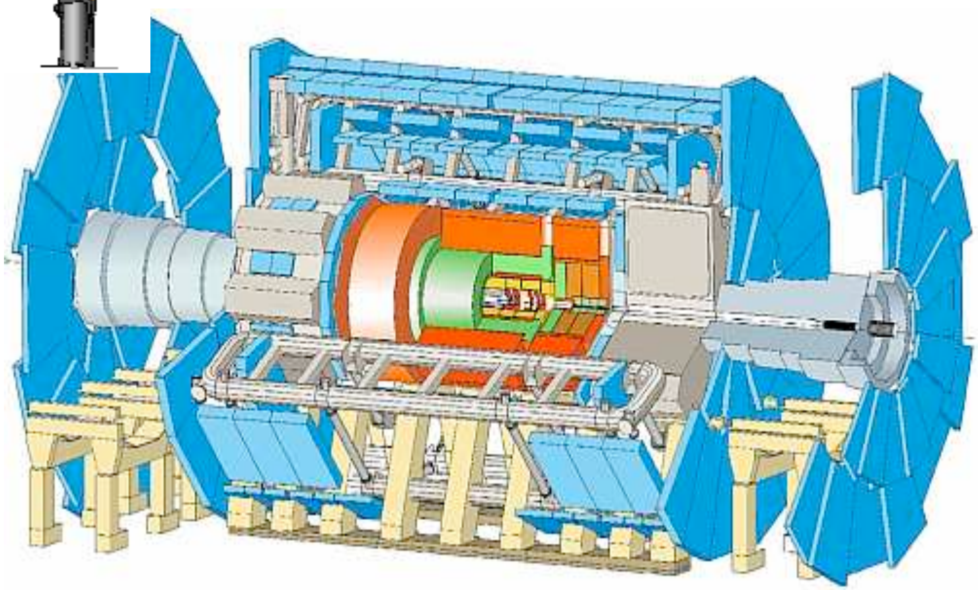


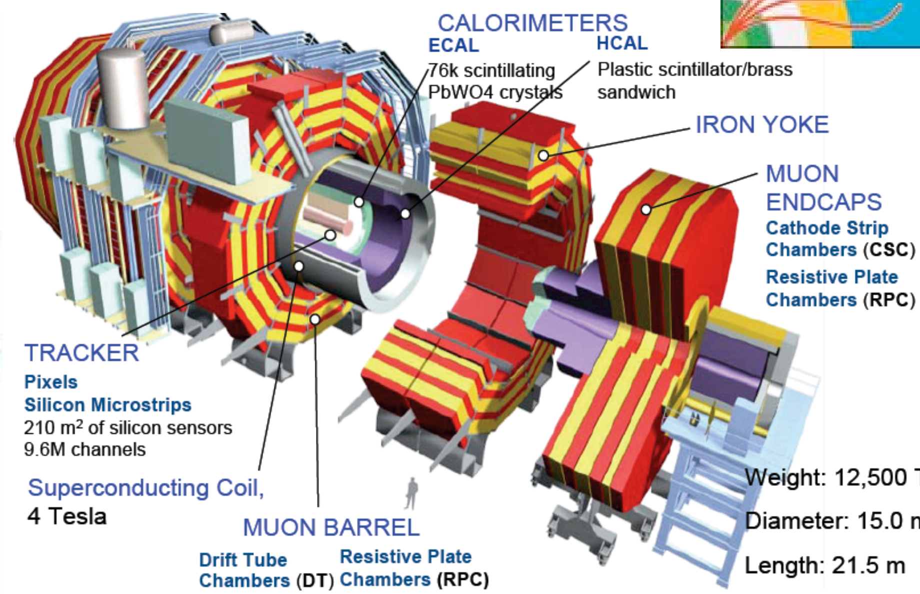
April 26th 2007
Descent of last magnet

| | |
|---|---|
| Cryostating | 425 FTE.years |
| Cold tests | 640 FTE.years |



# ATLAS and CMS Detectors



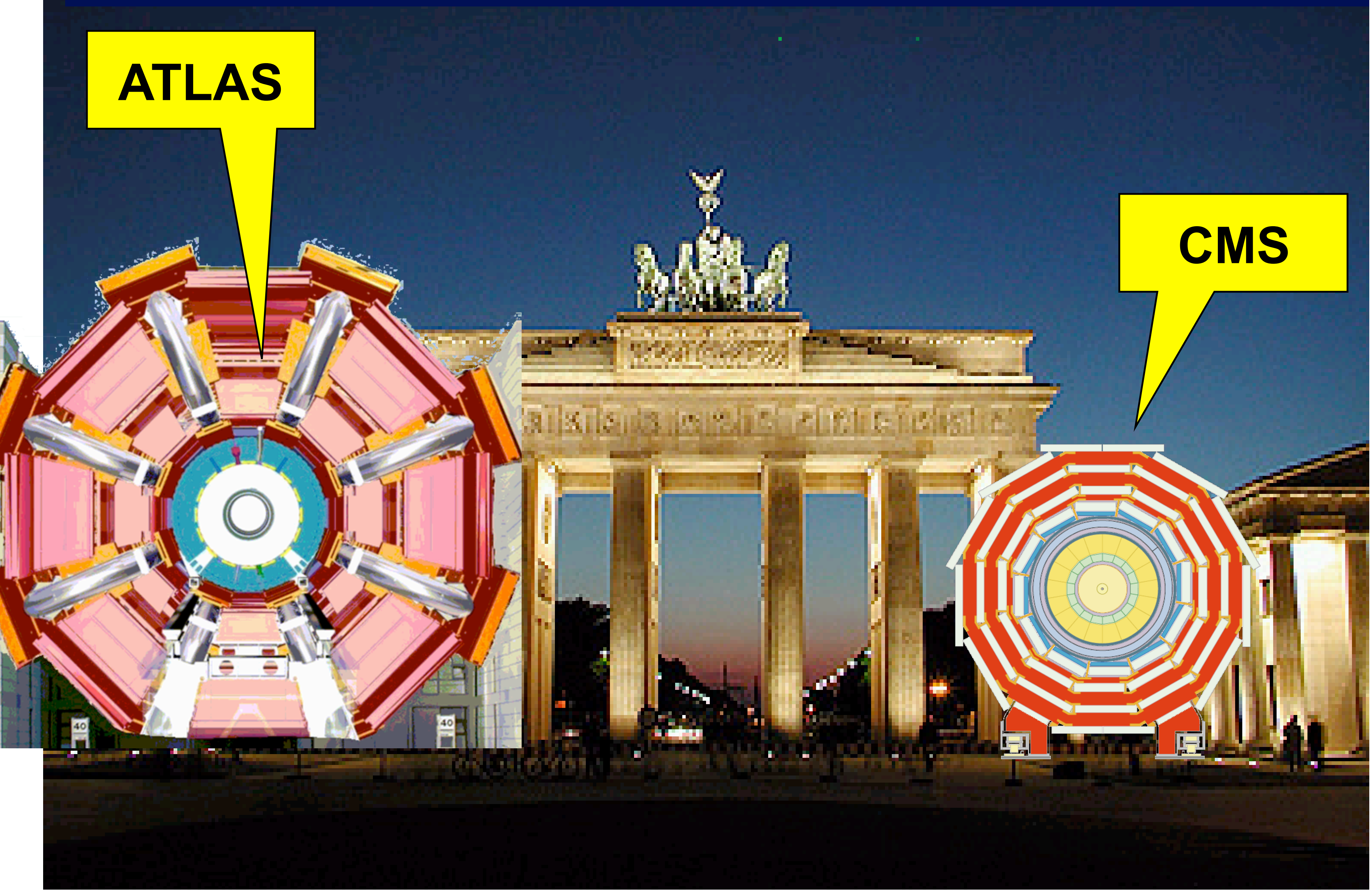




| | Weight (tons) | Length (m) | Height (m) |
|---|---|---|---|
| ATLAS | 7,000 | 42 | 22 |
| CMS | 12,500 | 21 | 15 |

**~2000 Scientists per experiment**
**+ many engineers and technicians**

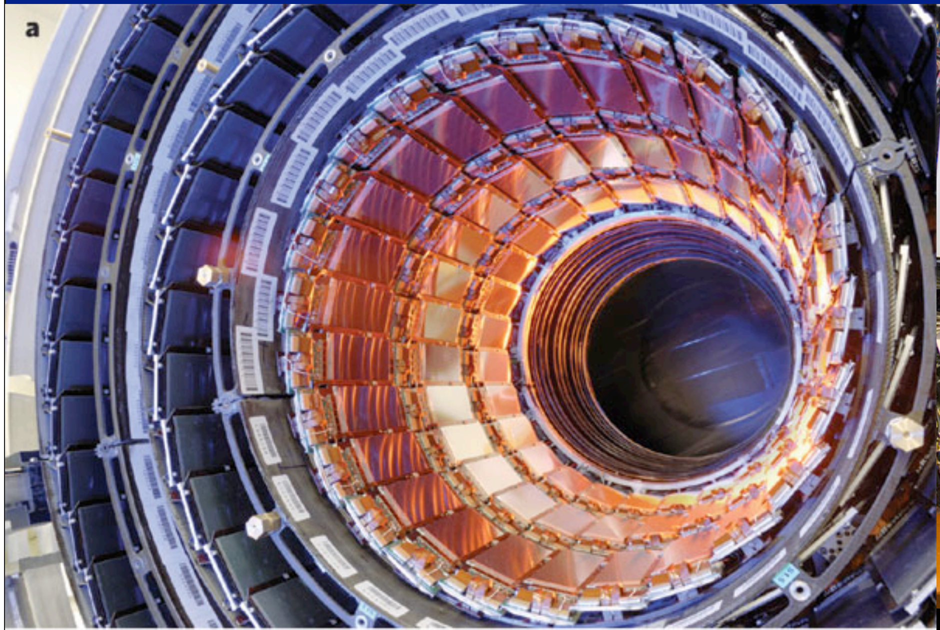
# ATLAS and CMS in Berlin

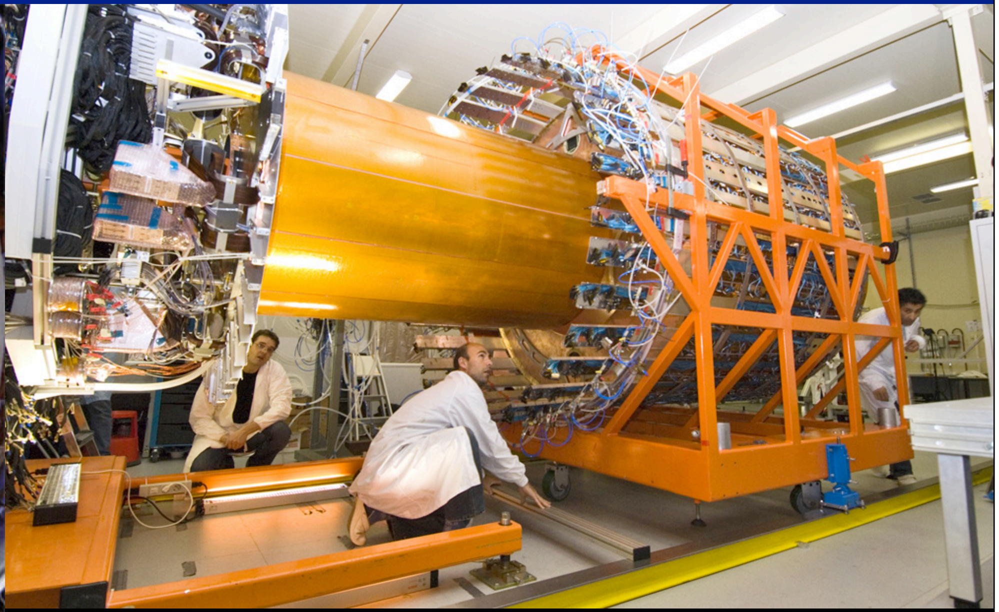


# Detector Mass in Perspective


**CMS is 30% heavier than the Eiffel tower**

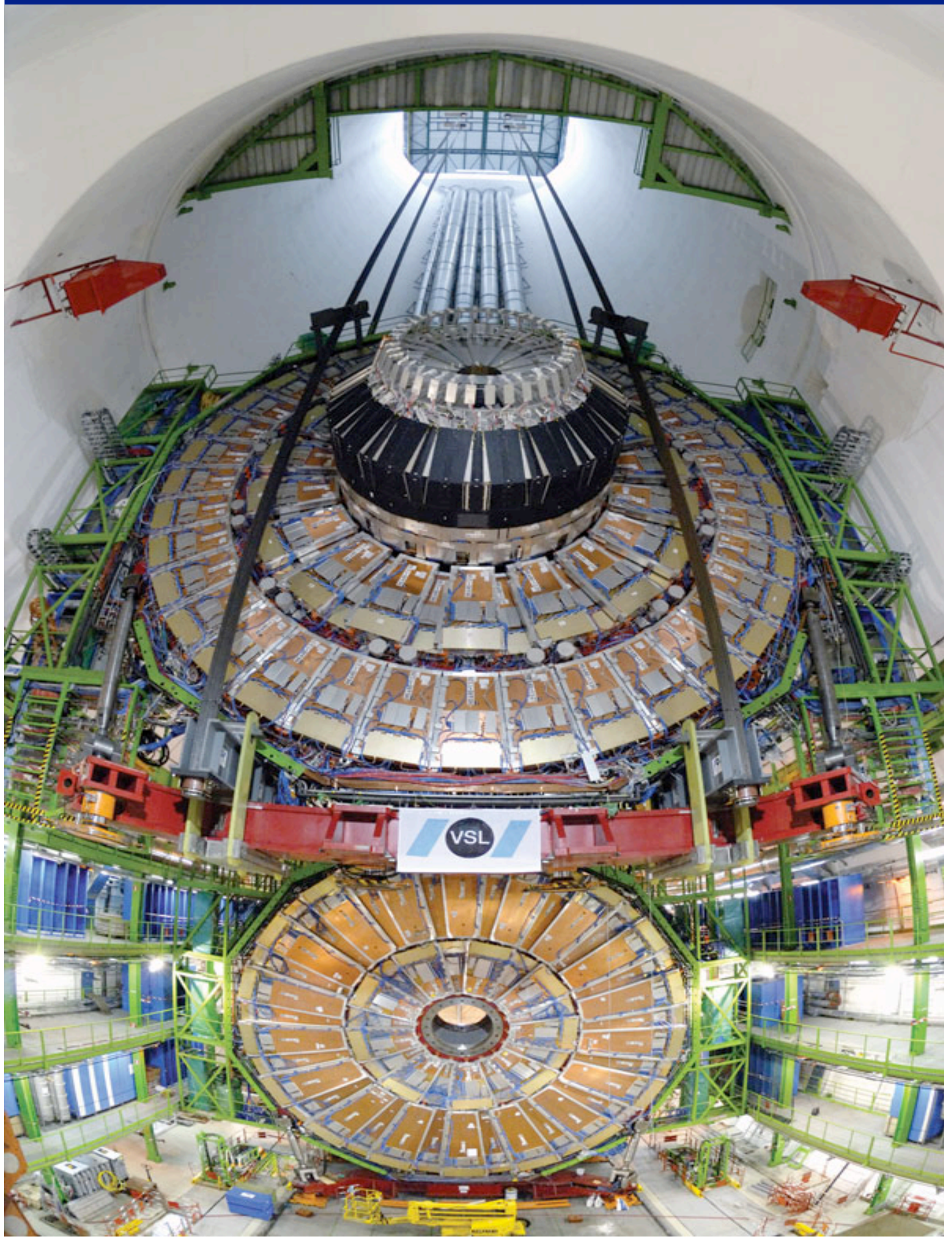
# Silicon Tracking Detectors

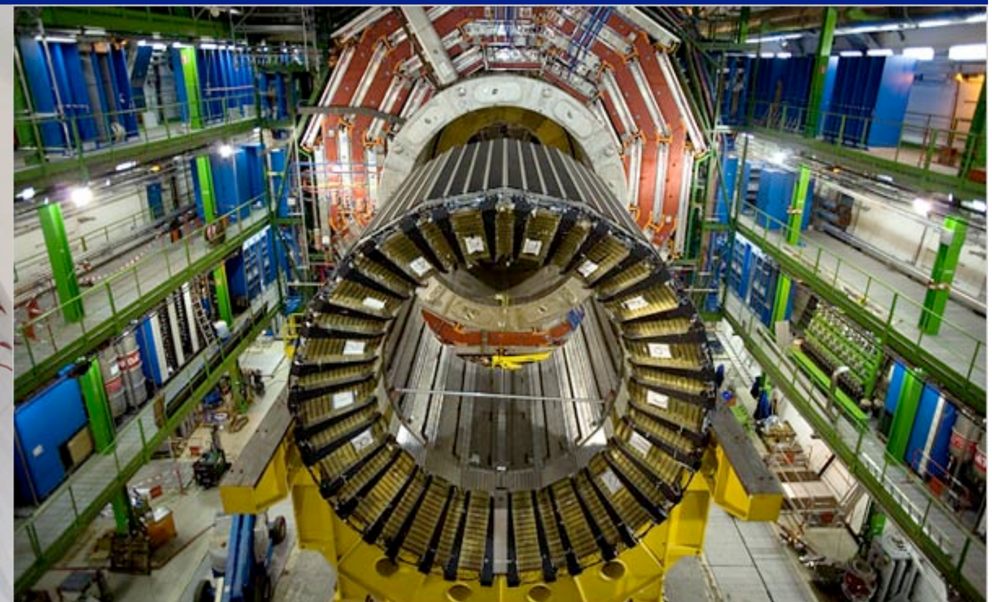


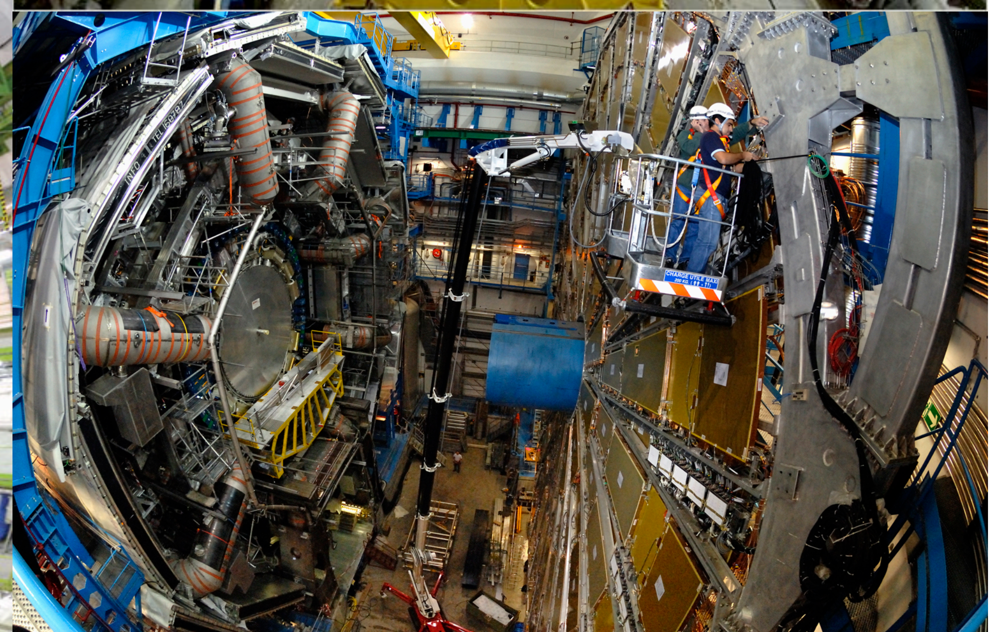




- Silicon strip and pixel detectors
  - Pixels used for first time at hadron colliders
  - Huge!
    - area of CMS silicon ~200 $m^2$
    - Like a football field!

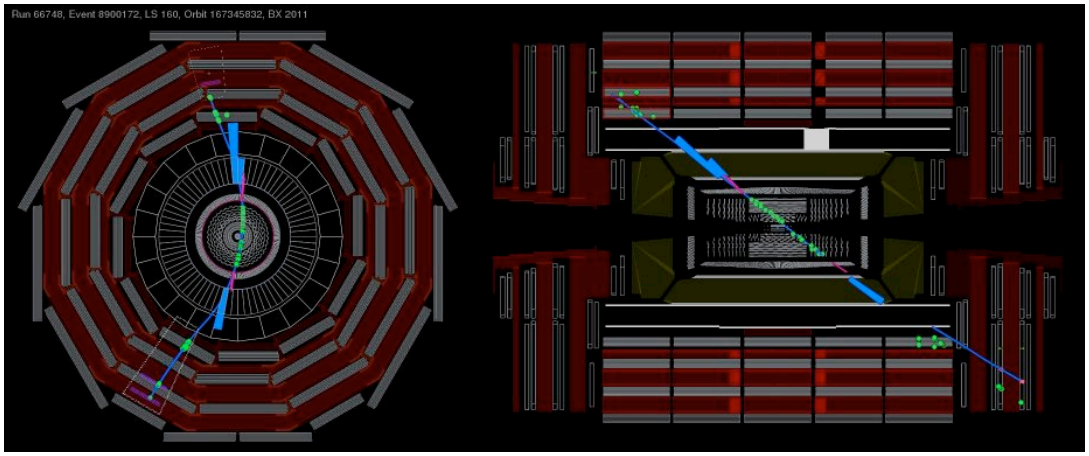
# Muon Systems and Calorimeters

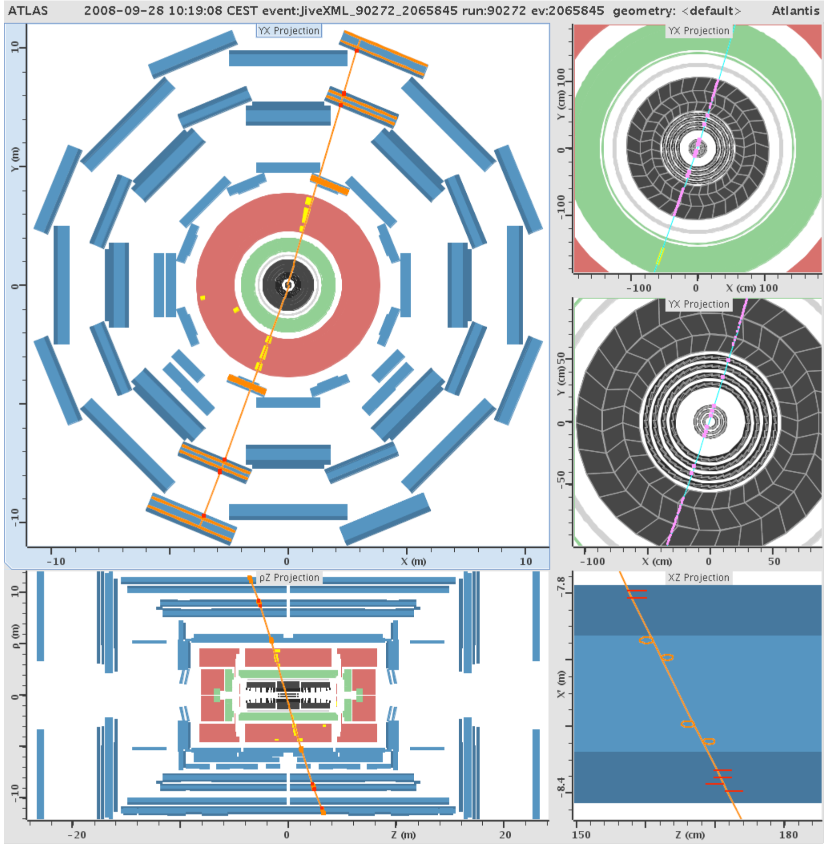




# Cosmic Data Taking End of 2008

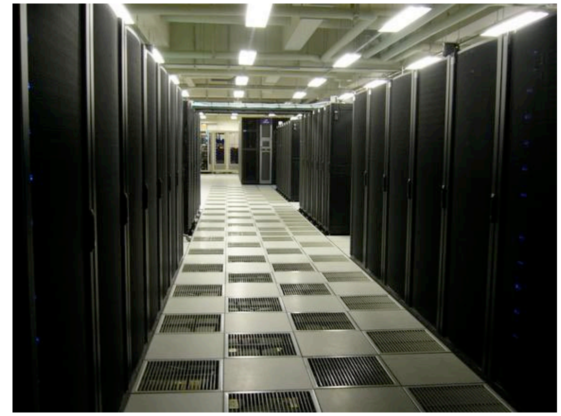


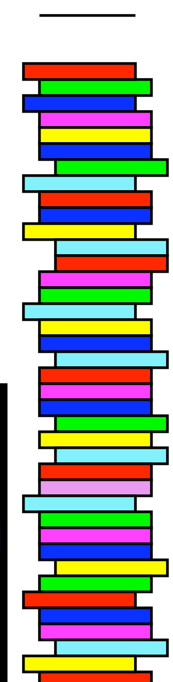




- After September incident
  - cosmic ray data taking of full detectors
  - Great operational experience
  - Allowed in-situ performance studies

# Enormous Data Volumes

- **Pushing the computing limits!**
  - 1 second of LHC data: 1,000 GigaBytes
    - **10,000 sets of the Encyclopedia Britannica**
  - 1 year of of LHC data: 10,000,000 GB
    - **25 km tower of CD's (~2 x earth diameter)**
  - 10 years of LHC data: 100,000,000 GB
    - **All the words spoken by humankind since its appearance on earth**





- **Solution: the "Grid"**
  - Global distribution of CPU power
    - More than 100 CPU farms worldwide share computing power

# Hadron-Hadron Collisions

# Calculating a Cross Section

- Cross section is convolution of pdf's and Matrix Element

Physical cross section

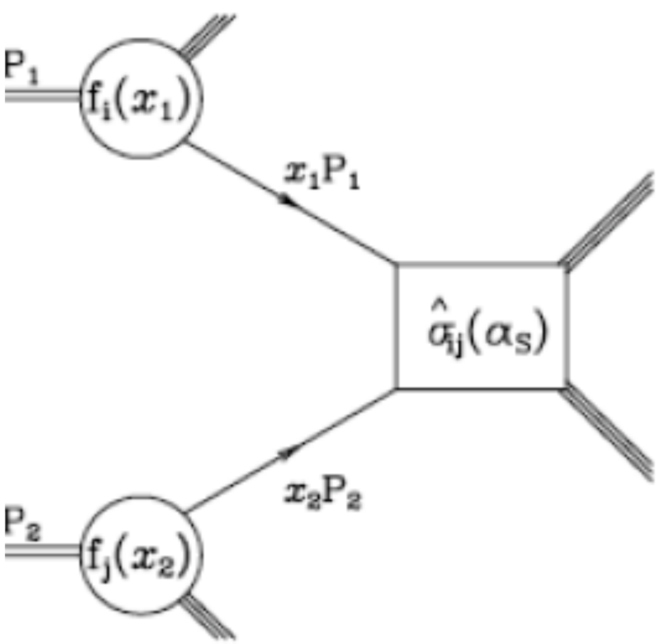
Parton distribution function

Renormalization scale $\mu_R$

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1, \mu_F) f_j(x_2, \mu_F)\, \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$

Factorization scale $\mu_F$

Short distance cross section, calculated as a perturbation series in $\alpha_S$

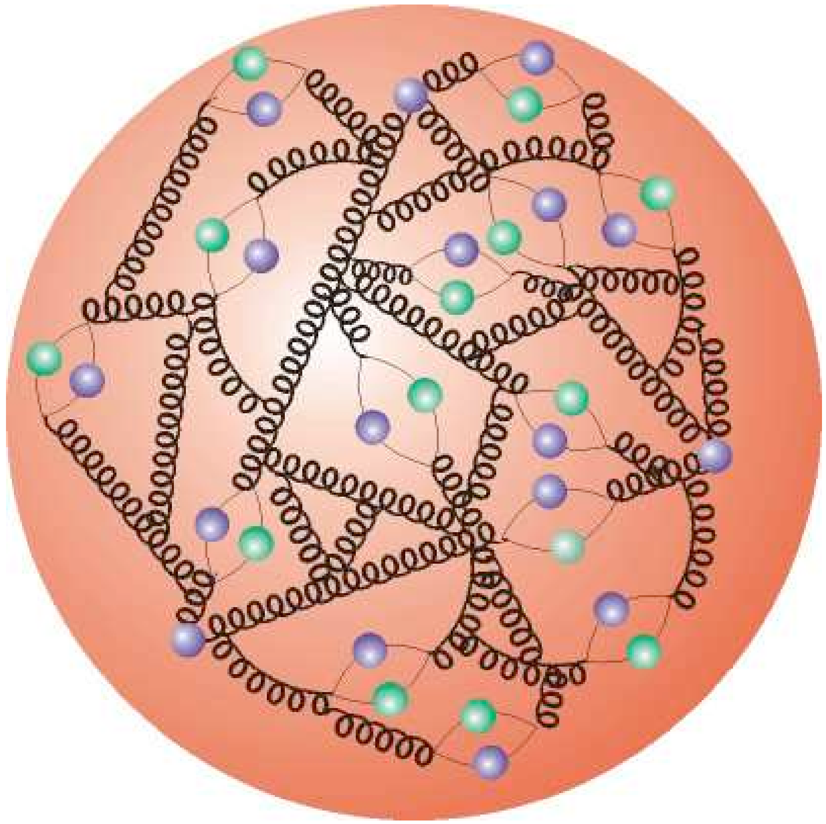


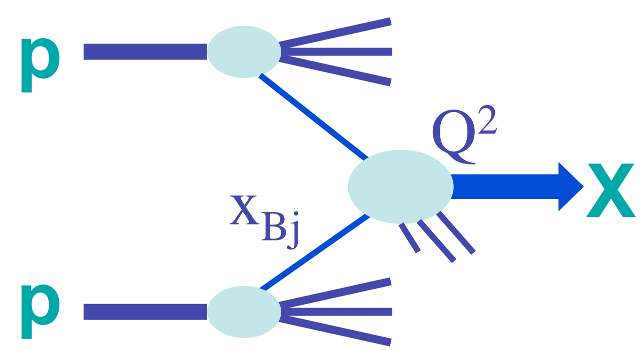

- Calculations are done in perturbative QCD
  - Possible due to factorization of hard ME and pdf's
    - Can be treated independently
  - Strong coupling ($\alpha_s$) is large
    - Higher orders needed
    - Calculations complicated

# The Proton Composition

- It's complicated:
  - Valence quarks, Gluons, Sea quarks
- Exact mixture depends on:
  - $Q^2$: ~$(M^2+p_T{}^2)$
  - Björken-x:
    - fraction or proton momentum carried by parton
- Energy of parton collision:

$$\boxed{\hat{s} = x_p \cdot x_{\bar{p}} \cdot s \qquad M_X = \sqrt{\hat{s}}}$$

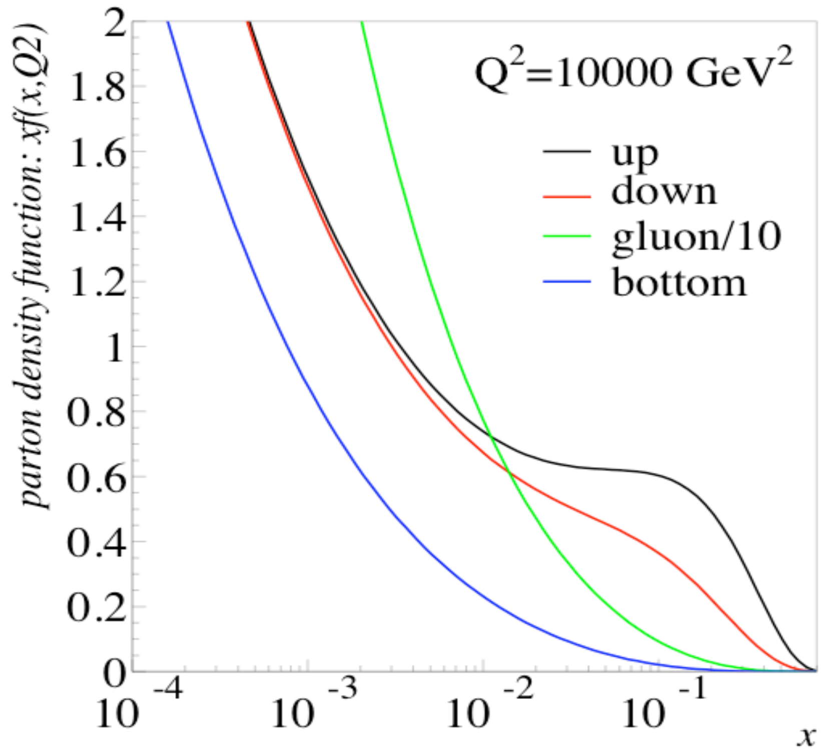




# Parton Kinematics

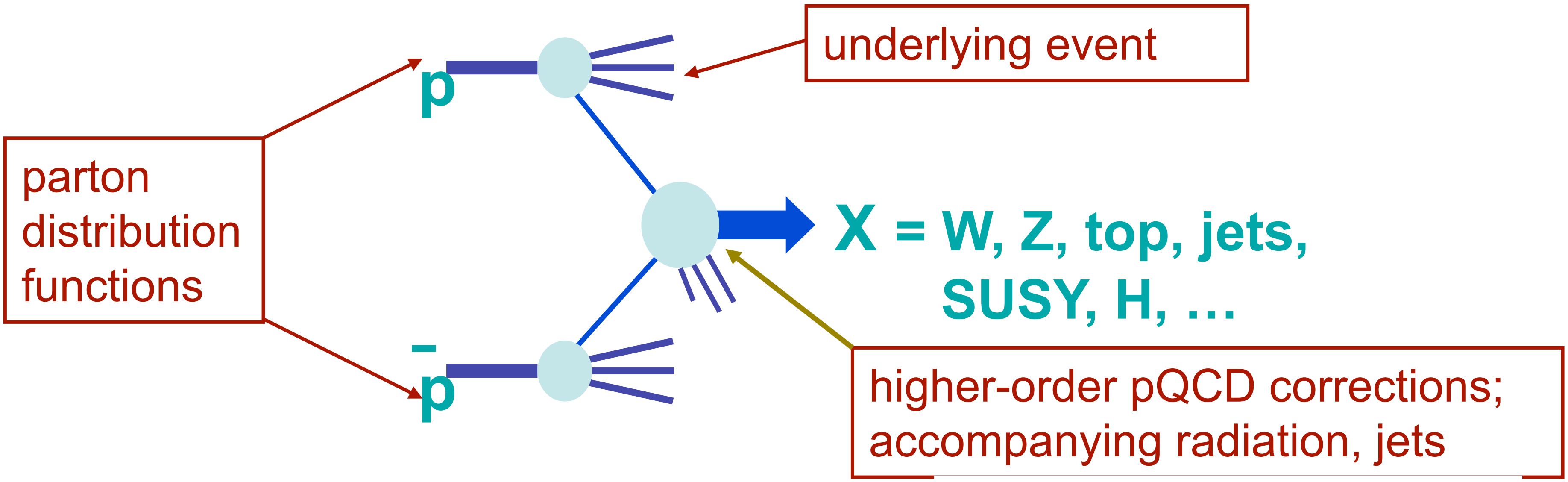
- Examples:
  - Higgs: M~100 GeV/$c^2$
    - LHC: $\langle x_p \rangle$=100/14000≈0.007
    - TeV: $\langle x_p \rangle$=100/2000≈0.05
  - Gluino: M~1000 GeV/$c^2$
    - LHC: $\langle x_p \rangle$=1000/14000≈0.07
    - TeV: $\langle x_p \rangle$=1000/2000≈0.5

pdf's measured in deep-inelastic scattering

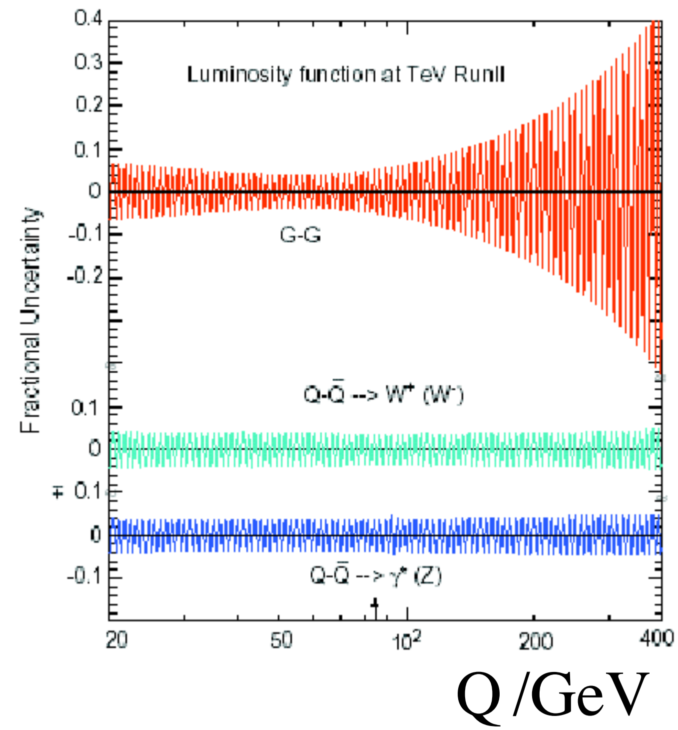



- Parton densities rise dramatically towards low x
  - Results in larger cross sections for LHC, e.g.
    - factor ~1000 for gluinos
    - factor ~40 for Higgs
    - factor ~10 for W's

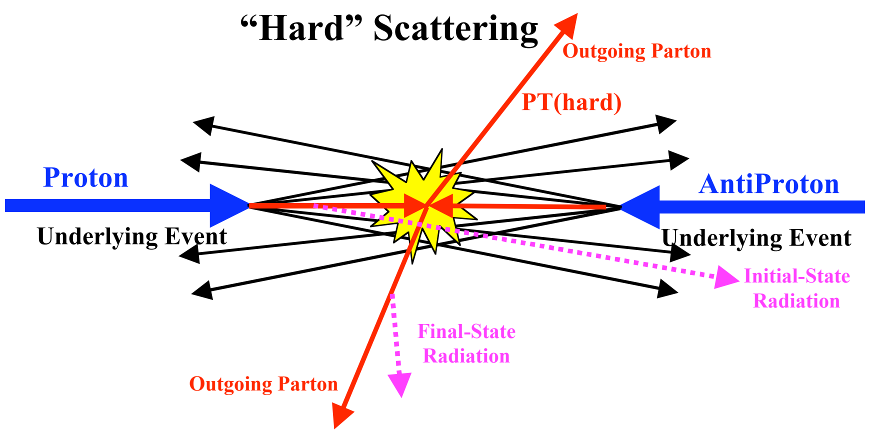
# The Proton is Messy



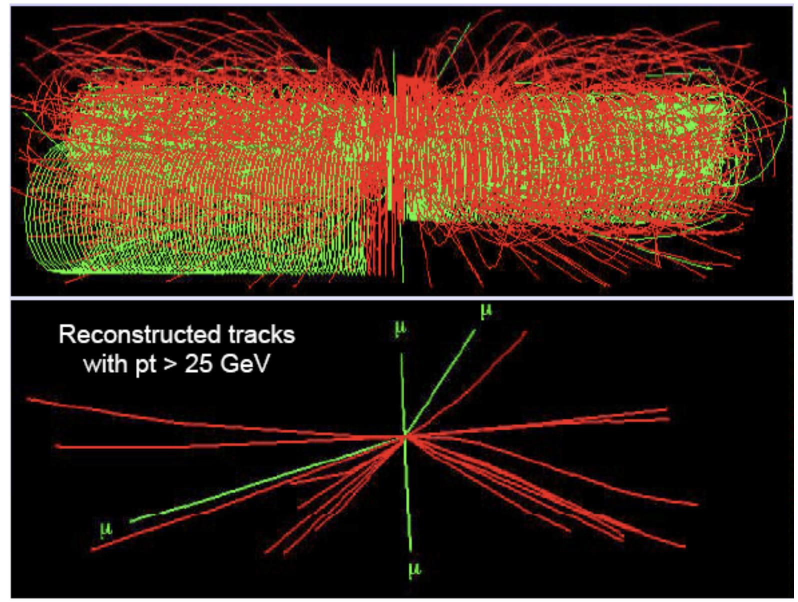

- We don't know
  - Which partons hit each other
  - What their momentum is
  - What the other partons do
- We know roughly (2-30%)
  - The parton content of the proton
  - The cross sections of processes



# Every Event is Complicated

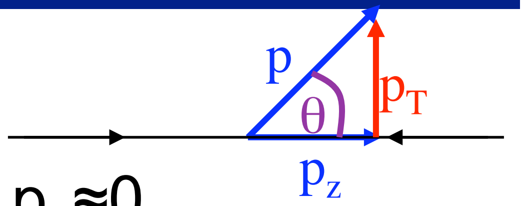



$H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-)$




- "Underlying event":
  - Initial state radiation
  - Interactions of other partons in proton
- Additional pp interactions
  - On average 20 at design luminosity of LHC
- Many forward particles escape detection
  - Transverse momentum ~0
  - Longitudinal momentum >>0

# Kinematic Constraints and Variables




- **Transverse momentum, $p_T$**
  - Particles that escape detection ($\theta<3^o$) have $p_T \approx 0$
  - Visible transverse momentum conserved $\sum_i p_T^i \approx 0$
    - **Very useful variable!**
- **Longitudinal momentum and energy, $p_z$ and E**
  - Particles that escape detection have large $p_z$
  - Visible $p_z$ is not conserved
    - **Not a useful variable**
- **Polar angle $\theta$**
  - Polar angle $\theta$ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: $\eta$

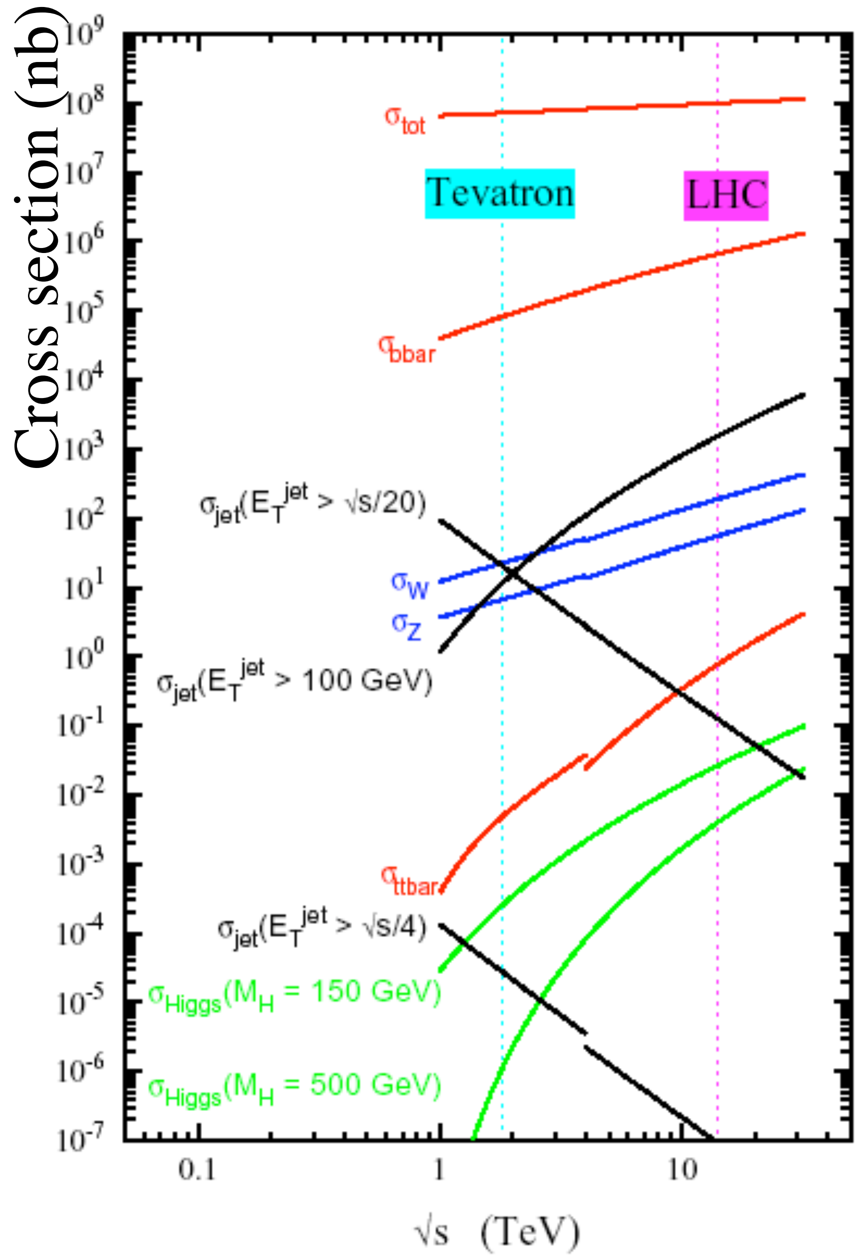
$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

For M=0

$$y = \eta = -\ln(\tan \frac{\theta}{2})$$

# Cross Sections at Tevatron and LHC

- A lot more “uninteresting” than “interesting” processes at design luminosity ($L=10^{34}$ $cm^{-2}s^{-1}$)
  - Any event: $10^9$ / second
  - W boson: 150 / second
  - Top quark: 8 / second
  - Higgs (150 GeV): 0.2 / second
- **Trigger** filters out interesting processes
  - Makes fast decision of whether to keep an event at all for analysis
  - Crucial at hadron colliders
- Dramatic increase of some cross sections from Tevatron to LHC
  - Improved discovery potential at LHC



# Conclusion of 1st Lecture

- Hadron Colliders
  - can address many of the problems with the Standard Model
    - Higgs boson
    - Physics beyond the Standard Model (e.g. Supersymmetry)
  - access higher energies than lepton colliders
    - Thus higher mass particles
  - are experimentally challenging
    - Many uninteresting background processes
    - The collisions themselves are complex
- Current colliders:
  - Tevatron is running since 2001
    - Planned to run at least until Fall 2010
  - LHC will start this year as the world's highest energy collider
    - 2009/2010 run: about 4 times higher energy than Tevatron

# Backup Slides

# Already happened in History!

*[H. Murayama]*

- Analogy in electromagnetism:
  - Free electron has Coulomb field: $\Delta E_{\rm Coulomb} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$
  - Mass receives corrections due to Coulomb field:
    - $(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\rm Coulomb}.$
    - With $r_e < 10^{-17}$ cm: $0.000511 = (-3.141082 + 3.141593)\ \mathrm{GeV}.$
  - Solution: the positron!

$$\Delta E = \Delta E_{\rm Coulomb} + \Delta E_{\rm pair} = \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e} \ .$$

**Problem was not as bad as today's but solved by new particles: anti-matter**

# Paul Dirac's View of History

When I first thought of the idea I thought that this particle would have to have the same mass as the electron, because of the symmetry between positive and negative masses and energies which occurs all the way through this theory. But at that time the only elementary particles that were known were the electron and the proton. I didn't dare to postulate a new particle. The whole climate of opinion in those days was against postulating new particles, quite different from what it is now. So I published my work as a theory of electrons and protons, hoping that in some unexplained way the Coulomb interaction between the particles would lead to the big difference in mass between the electron and the proton.

Of course I was quite wrong there and the mathematicians soon pointed out that it was impossible to have such a dissymmetry between the positive and negative energy states. It was Weyl who first published a categorical statement that the new particle would have to have the same mass as the electron. The theory with equal masses was confirmed a little later by observation when the positron was discovered by Anderson.

# Luminosity Measurement

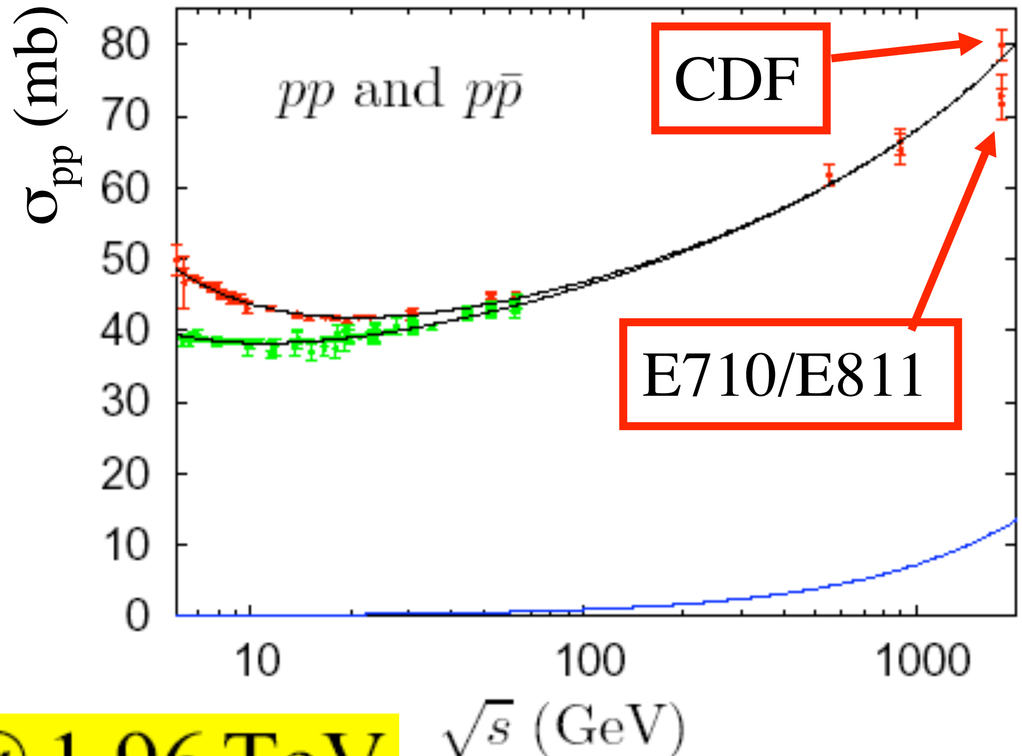
$$R_{pp} = \mu_{pp} \cdot f_{BC} = \sigma_{inel} \cdot \varepsilon_{pp} \cdot \delta(L) \cdot L$$

$\sigma_{LM}$

$L$ – luminosity
$f_{bc}$ – Bunch Crossing rate
$\mu_a$ – # of pp / BC

$\sigma_{inel}$ – inelastic x-section
$\varepsilon_{pp}$ – acceptance for a single pp
$\delta(L)$ – detector non-linearity

- Measure events with 0 interactions
  - Related to $R_{pp}$
- Normalize to measured inelastic pp cross section




$$\overline{\sigma}_{in} = 60.7 \pm 2.4mb\ @\ 1.96\ \text{TeV}$$